TNO Defence, Security and Safety

Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek / Netherlands Organisation for Applied Scientific Research

Oude Waalsdorperweg 63
P.O. Box 96864
2509 JG Den Haag
The Netherlands

www.tno.nl

T +31 70 374 00 00
F +31 70 328 09 61
info-DenV@tno.nl

TNO report

TNO-DV1 2005 A044

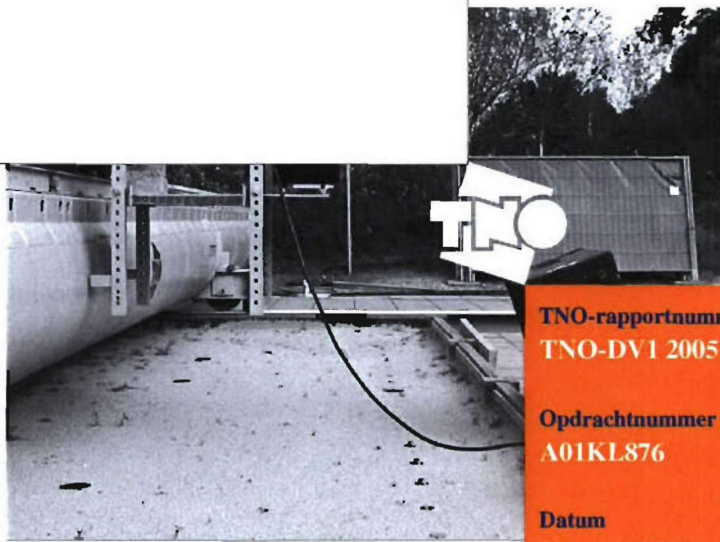
Landmine detection using laser vibrometry

Date	January 2006
Author(s)	Dr. J.C. van den Heuvel Ir. A.C. van Koersel Ing. F.J.M van Putten Dr. ir. H.M.A Schleijpen
Classification report	ongerubriceerd
Classified by	Maj. L Lagerwerf
Classification date	
Title	Ongerubriceerd
Managementuittreksel	Ongerubriceerd
Abstract	Ongerubriceerd
Report text	Ongerubriceerd
Appendices	Ongerubriceerd
Copy no	8
No. of copies	14
Number of pages	58 (incl. appendices, excl. RDP & distributionlist)
Number of appendices	2

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

MANAGEMENTUITTREKSEL

Landmine detection using laser vibrometry



TNO-rapportnummer
TNO-DV1 2005 A044

Opdrachtnummer
A01KL876

Datum
Januari 2006

Auteur(s)
Dr. J.C. van den Heuvel
Ir. A.C. van Koersel
Ing. F.J.M. van Putten
Dr. ir. H.M.A. Schleijpen

Rubricering rapport
Ongerubriceerd

Probleemstelling

De Koninklijke Landmacht wil op het gebied van mijnbestrijding optreden als smart buyer en smart user. Om hiertoe in staat te zijn is het noodzakelijk om diepgaande technische kennis van mijnbestrijdingsystemen te hebben. Mechanische ruim- en bestrijdingsmiddelen zijn reeds beschikbaar. De grootste vooruitgang is te boeken op het gebied van detectiemiddelen. De huidige detectietechnieken zijn grotendeels gebaseerd op bestaande commercieel verkrijgbare sensoren. Dat betekent dat er beperkingen zullen zijn aan het maximaal haalbare resultaat. Op langere termijn kunnen echter nieuwere technieken worden ontwikkeld die de resultaten verder kunnen verbeteren.

De studie naar de nieuwe detectiemethode zoals beschreven in dit rapport is uitgevoerd door TNO Defensie en Veiligheid, locatie Den Haag onder het programma Mijnbestrijding (V011). Dit programma heeft tot doel ertoe bij te dragen dat voor Defensie adequate kennis ter beschikking komt ter ondersteuning bij de aanschaf en inzet van middelen om mijnendetectie en mijnbestrijding veilig en efficiënt uit te voeren, zowel in grootschalige conflicten als in vredesoperaties.

Beschrijving van de werkzaamheden

Twee methoden zijn onderzocht voor het detecteren van begraven landmijnen op basis van geluidsmetingen aan het oppervlak met een laservibrometer. In de eerste methode (akoestische excitatie) wordt de grond in trilling gebracht door middel van een grote luidspreker; de laservibrometer meet het verschil in trilling van een oppervlak met en zonder begraven mijn. Bij de tweede methode (laserexcitatie) wordt de grond in trilling gebracht door middel van een korte laserpuls waarna de laservibrometer het tijdsverloop van de trilling aan het oppervlak meet en hiermee de begraven mijn probeert te detecteren.

Het onderzoek is uitgevoerd in samenwerking met het Duitse instituut FOM van FGAN onder de samenwerking DNAP TV-7. In een gezamenlijk veldexperiment zijn beide methoden getest op simulantmijnen met de originele behuizing maar met een vervangend materiaal voor de explosieve lading.

Resultaten en conclusies

De akoestische excitatie is goed bruikbaar om begraven mijnen te detecteren hoewel de methode te langzaam is voor combinatie met andere detectiesensoren. Echter, de methode is goed bruikbaar als verificatiesensor waarbij nieuwe informatie wordt verkregen in vergelijk met traditionele methoden als metaaldetectie.

Laserexcitatie is een weinig onderzochte methode die in potentie een snelle detectiemethode mogelijk maakt. Tevens is deze methode beter geschikt voor stand-off-detectie dan de akoestische excitatie. Uit onze experimenten blijkt echter dat oppervlakte-effecten, zoals wegschietende gronddeeltjes ten gevolge van de laserexcitatiepuls, de metingen verstoren. Hierdoor is er een grote variatie van puls tot puls, waardoor niet of nauwelijks het verschil tussen situaties met of zonder begraven mijn is te detecteren.

Toepasbaarheid

De resultaten laten zien dat landmijndetectie door middel van trillingsmetingen aan het grondoppervlak met een laservibrometer mogelijk is als wordt gebruikgemaakt van akoestische excitatie. In dit geval is de techniek een goede (maar langzame) verificatiemethode.

PROGRAMMA	**PROJECT**
Programmabegeleider Maj. L. Lagerwerf, KL OTC Genie	Projectbegeleider Maj. L. Lagerwerf, KL OTC Genie
Programmaleider H.M.A. Schleijpen, TNO-DV	Projectleider J.C. van den Heuvel, TNO-DV
Programmatitel Mijnbestrijding	Projecttitel Landmijnen en lasers
Programmanummer V011	Projectnummer 015.31606
Programmaplanning Start 1 januari 2001 Gereed 31 december 2004	Projectplanning Start 1 juni 2001 Gereed 31 december 2004
Frequentie van overleg Halfjaarlijks programmaoverleg Rond veldexperiment en conferentie artikelen wekelijks overleg	Projectteam Dr. J.C. van den Heuvel Ir. A.C. van Koersel Ing. F.J.M. van Putten Dr. ir. H.M.A. Schleijpen Ing. L.H. Cohen Ir. G.J. Kunz

Contents

1 Introduction

Reliable and rapid detection of buried land mines – be it antitank mines (ATM) or antipersonnel mines (APM) – was and is a challenging task for the military as well as the civilian community. In this report a comparison is made of two acoustic landmine detection (ALD) techniques: acoustic excitation and laser excitation both with a Laser Doppler Vibrometer (LDV) for the detection of surface vibration. Both techniques are valuable in a sensor fusion concept since they provide complementary information about buried objects with respect to GPR or metal detectors.
Acoustic landmine detection (ALD) is a promising detection method, since it does not depend on the metal content of landmine. Thus, metal mines as well as plastic mines (e.g. anti-personnel) can be detected, since this approach is absolutely independent of any metal content within a mine. This is valid for a variety of soil types including soils with ferromagnetic content. Chapter 2 gives a review of the literature on ALD.
There are two excitation methods studied in this report: acoustic excitation and laser excitation. The main use of ALD with acoustic excitation is as an additional verification sensor in a sensor fusion concept. Figure 1.1 shows the principle of the technique with an experimental result. A loudspeaker generates a sound wave that brings the soil into vibration. With a scanning LDV the amplitude of the surface vibration is measured. The vibration amplitude is shown in an intensity plot, which clearly shows the shape of the buried mine.

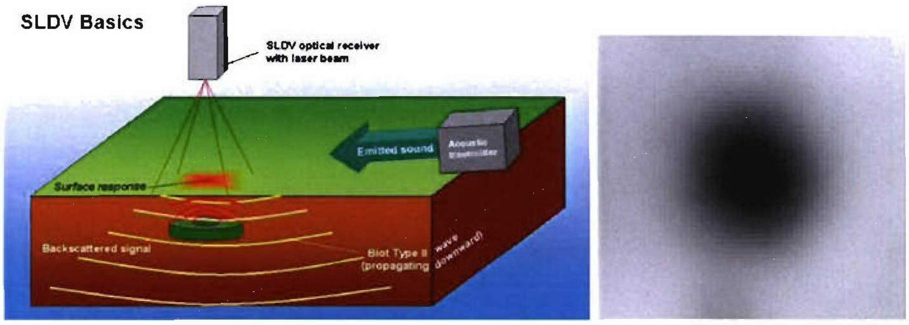


Figure 1.1: Principle of acoustic excitation (left) with result on ATM showing intensity image of vibration amplitude (ATM is dark).

With ground-penetrating radar, objects embedded in the soil present a dielectric variation and cause a reflection of the electromagnetic wave. This permits a 3D-mapping of the ground, but does not give specific frequency "fingerprints" from objects as does the 2D-mapping by the scanning LDV with acoustic excitation. The acoustic excitation gives a good contrast between the buried mine and the surrounding soil at certain frequencies. Chapter 3 gives an overview of the technique.
ALD with laser excitation gives a pulse response that is more difficult to interpret than the acoustic excitation but is potentially a faster technique. Figure 1.2 shows the principle of the technique with an experimental result. The vibration of the soil is generated by a short laser pulse that heats the surface. This vibration is measured by an LDV. The vibration amplitude versus time is plotted and peaks after the first surface peak suggest the presence of a buried mine.

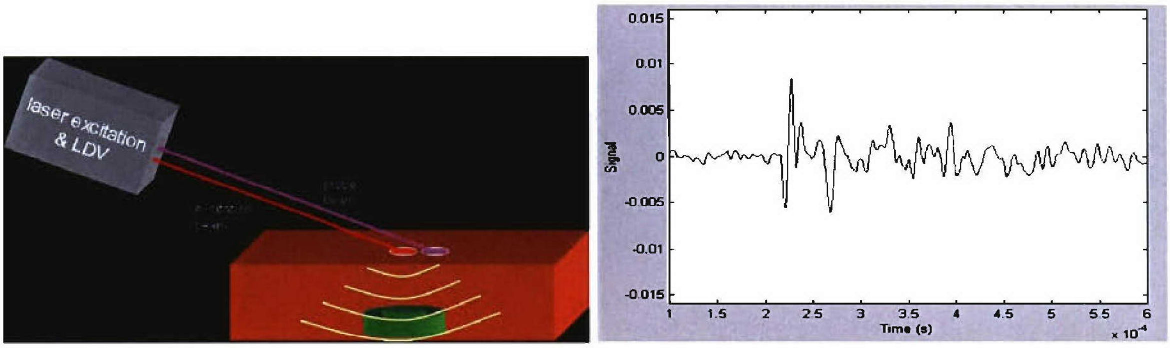


Figure 1.2: Principle of laser excitation (left) with result on ATM showing a possible echo of the ATM.

In chapter 4 it is shown that laser excitation gives a reproducible acoustic excitation at the surface and that the acoustic excitation is coupled into the ground. Using the Laser Doppler Vibrometer (LDV) to measure the acoustic signal at the surface, we found a clear signal of the first peak corresponding to the acoustic surface excitation propagating along the surface. However, the LDV signal after the first peak shows large shot-to-shot variation making detection of buried objects difficult. These shot-to-shot variations are caused by surface effects that are prominent in LDV signals but are negligible in microphone signals. This is a severe limitation in the use of an LDV system in combination with laser excitation for ALD.

2 Literature survey

At the start of the project a literature survey was performed to assess the feasibility of acoustic landmine detection.

2.1 List of studied articles

1. Yan Qing Zeng, Acoustic Detection of Buried Objects in 3-D Fluid Saturated Porius Media: Numerical Modeling; remore Sensing , vol 39, no 6, june 2001.
2. Y.Q. Zeng, Q.H. Liu, Acoustic landmine detection: a 3D poroelastic model, SPIE vol 4394, pp. 583-594.
3. D. Velea, C. Hickey, J.M. Sabatier, Acoustic scattering by buried objects in a rigid porous material, SPIE vol 4394, pp.595-606.
4. Thomas R. Witten et.al., Acoustic Technology for Landmine Detection - Past Tests, Present Requirements, and Future Concepts; Proc SPIE vol. 4038 (2000).
5. James M. Sabatier and Ning Xiang, An Investigation of Acoustic-to-Mine Coupling to Detect Buried Antitank Landmines; IEEE Transactions on Geosc. and Rem. Sens.,Vol.39, No.6, June 2001.
6. Ning Xiang and James M. Sabatier, Anti-personnel mine detection using acoustic-to-seismic coupling; Proc. SPIE Vol. 4394 (2001).
7. R. Daniel Costley et.al., Continuous scanning laser doppler vibrometer for mine detection; Proc. SPIE vol. 4038, April 2000.
8. Dimitri M. Donskoy, Detection and discrimination of nonmetallic land mines; Proc. SPIE Vol.3710, April 1999.
9. G.D. Larson, J.S. Martin, W.R. Scott Jr, G.S. McCall II, Environmental Factors that impact the performance of a Seismic Land Mine Detection System, SPIE vol 4394, pp. 563-574.
10. Waymond R. Scott et.al., Experimental Model for a Seismic Landmine Detection System; IEEE Transactions on Geosc. and Rem. Sens. Vol.39, No.6, June 2001.
11. R. daniel Costley et.al.,Forward-looking acoustic mine detection system; Proc. SPIE Vol.4394 (2001).
12. M. Bradley et.al.,Fusion of Acoustic/Seismic and Ground Penetrating Radar Sensors for Antitank Mine Detection;
13. Witten et.al. Imaging and Detection of Mines from Acoustic Maeasurements; Proc. SPIE Vol. 3710,April 1999
14. S.W. McKnight and C.A. DiMarzio,Imaging of Buried Objects by Laser-Induced Acoustic Detection; Proc. SPIE Vol.3710, April 1999.
15. Paul M. Goggans et.al.,Increasing Speckle Noise Immunity in LDV-Based Acoustic Mine Detection; Proc. SPIE 4038 (2000)
16. Ning Xiang and James Sabatier,Land mine detectoin measurements using acoustic-to-seismic coupling; Proc. Spie Vol.4038 (Apr. 2000)
17. W. DiMarzio and S.W. McKnight, Laser-induced Acoustic Detection of Shallow-Buried Objects, Proc. SPIE Vol.3752, July 1999
18. S.W. McKnight et.al., Laser-induced acoustic generation for buried object detection, Proc. SPIE Vol. 4038 (2000)

19. J.M. Sabatier and N. Xiang,Laser-Doppler Based Acoustic-to-Seismic Detection of Buried Mines Proc. SPIE Vol.3710, April 1999
20. S.W. McKnight, J. Stott, C.A. DiMarzio, R Cleveland, R. Roy, Laser-induced acoustic imaging of buried land mines: experiment and modeling, SPIE vol 4394, pp. 627-633.
21. D. Donskoy et.al., Nonlinear Seismo-Acoustic Land Mine Detection: Method and Instrumentation;
22. D. Donskoy, N. Sedunov, A. Ekimov, M. Tsionskiy, Optimization of seimo-acoustic land mine detection using dynamic mechanical impedances of mines and soil, SPIE vol 4394, pp.575-582.
23. Erik M. Rosen et.al.,Performance Assessmentr of a Blind Test Using the University of Missisippi's Acousto/Seismic Laser Doppler Vibrometer (LDV) Mine Detection Apparatus at Fort A.P. Hill, Proc SPIE Vol.4038 (April 2000)
24. C.T. Schroder and W.R. Scott, Jr., Resonance Behaviour of Buried Land Mines; Proc. SPIE Vol. 4394 (2001)
25. L. Dwynn Lafleur et.al.,Shape Discrimination of buried objects using an acoustic land mine detection system; Proc SPIE Vol. 4038 (Apr., 2000)
26. Nesbitt W. Hagood, Scanning Laser Vibrometry System;
27. P.M. Goggans and C.R. Smith,Signal Processing of Laser-Doppler Vibrometer Output for Mine Detection; Proc. Spie Vol. 3710 (Apr., 1999)
28. Charles A. DiMarzio et.al., Toward a Laser-Based, Non-Contact Acoustic Landmine Imager; Proc. SPIE Vol. 4038 (Apr., 2000)
29. W.R. Scott Jr, S.H. Lee, G.D. Larson, J.S. Martin, G.S. McCall II, Use of High-Frequency Seismic Waves for the Detection of Buried Land Mines, SPIE vol 4394, pp. 543-552.

2.2 General comments

17. W. DiMarzio and S.W. McKnight, Laser-induced Acoustic Detection of Shallow-Buried Objects, Proc. SPIE Vol.3752, July 1999

Laser excitation	x	Laser receiver	x	Other sensors	
Acoustic excitation		Acoustic receiver	x	Theory	

A CO_2 laser was used to couple acoustic energy in the soil. Different acoustic receivers were used including a laser vibrometer. The articles claims that the LDV is the best receiver due to higher frequency response and the better integration with the laser excitation. In sand an attenuation of 90 m^{-1} is found, thus the technique is only useful for shallow buried mines (1/e at 1 cm). Depth information is not extracted from the acoustic pulse shape (probably only shallow mines).

12. M. Bradley et.al.,Fusion of Acoustic/Seismic and Ground Penetrating Radar Sensors for Antitank Mine Detection;

Laser excitation		Laser receiver	X	Other sensors	GPSAR
Acoustic excitation	X	Acoustic receiver		Theory	

LDV measurements show a clear signature up to a burial depth of six inches for an antitank mine. Frequency range is 80 – 200 Hz. GPSAR has is better in deeply buried mines (up to six inches), LDV performs poor here.

4. Thomas R. Witten et.al., Acoustic Technology for Landmine Detection - Past Tests, Present Requirements, and Future Concepts; Proc SPIE vol. 4038 (2000).

Laser excitation		Laser receiver	X	Other sensors	
Acoustic excitation	X	Acoustic receiver		Theory	

Optimum frequency for an antitank mine is 175 Hz, for an antipersonnel mine this is in the range 300-400 Hz. A 30-degree depression angle was acceptable, however at 12-degree distortion occurred. Claimed is that the technique works for short grass and vegetation. It seems that the technique is immune to buried stones. A rule of thumb is that the radius of the mine must be greater that the burial depth for detection. Specific attention is given to the speed of the measurement. Since the technique is rather slow, increase of the speed is required which could be achieved by using multiple beams. Several system concept are proposed.

6. Ning Xiang and James M. Sabatier, Anti-personnel mine detection using acoustic-to-seismic coupling; Proc. SPIE Vol. 4394 (2001).

Laser excitation		Laser receiver	X	Other sensors	
Acoustic excitation	X	Acoustic receiver		Theory	

The problem of anti-personnel mine detection and discrimination between mines and clutter is addressed. Mine responses are broad band while clutter is mostly narrow band. In the case of broadband clutter the shape of the detection is used.

2.2.1 *General observations*

All papers use commercially available LDV sensors and do not describe the LDV sensor. It is possible that better results could be achieved by optimising the LDV sensor both in speed and sensitivity.

Few papers describe the laser excitation in contrast to the acoustic excitation. No results on depth profiling with laser excitation was found.

Signal processing of the LDV sensor data does not receive much attention.

Detection depth ranges from 1 cm to 30 cm.

2.3 Aspects concerning acoustics

There are several methods for the soil excitation and for the registration of the reflected acoustical signal from buried objects. A number of combinations of these methods are reported.

1 Acoustic excitation of the soil using broadband low-frequency noise from loudspeakers, and the registration using LDV (Sabatier 1, 4, 6). In addition one or two microphones are used for registration (Don&Lawrence, see abstract 1).

2 Acoustic excitation of the soil with a laser, a measuring the acoustic signal with a piezo sensor (in the ground) or an electret microphone (above the ground) or with a laser from a distance. (McKnight 8)
3 Acoustic excitation of the soil with a shaker that generates an elastic surface wave and using a radar for registration. (Scott 2, 3, 10)
4 Donskoy (7) also studied the modelling of the mine-soil system using a damped-spring model. Furthermore, Donskoy presented at SPIE in 1998 (see 11) a new technique that is based on the non-linearity of the medium, which gives sum and difference frequencies in the medium. Thus low frequency waves are generated from two high frequency waves with a small frequency difference. At SPIE 2002 new result with this technique were shown by Donskoy (4742-77) and Sabatier (4742-79). A patent was obtained on this technique.

Most papers on method 1 are from Sabatier of the university of Mississippi. Sabatier has worked on this method from medio 1996, first with a stationary set-up, later with a stop-and-stare system. Modelling of the mine-soil interaction under an acoustic excitation is done with a damped spring model. In this model the soil above the mine, the mine, and the soil around the mine is represented in the model. The model output is a frequency plot with poles and zeros that are observed in the experiments. Most of these poles and zero in frequencies occur in the range of 80 and 300 Hz (Gader, SPIE 2002 [4742-72]). This has been explained by Su Hsin-Yu (SPIE 2002 [4742-80]) using a state-space-model and the corresponding poles and zeros.
New developments on method 1 were presented by Amit Lal [4742-72] with classification based on images from Gadar [4742-72] and detection with a forward moving LDV from Writer [4742-73].

Method 2 is described by a paper of McKnight (8) including a number of experimental results in a sand field. The acoustic signal generated by the laser was registered by a piezo sensor and a microphone. They propose to measure the acoustical signal with an LDV, since only a small part of the scattered acoustic energy in coupled into the air.

Waymond Scott presentated at SPIE 2002 method 3, i.e. the use of an array of radar sensors to register the vibration of the ground. Scott showed results of measurements using two radar sensors. Attention was given to the design of the radar antenna: a corrugated horn with relief on the horn to adapt the impedance. As a vibration source, a seismic shaker was used that transmitted a puls shape (wavelet). The surface or Rayleigh wave is transmitted through the soil and is scattered at the mine. A number of videos of the measured signals were presented.

1 Ning Xiang and James M. Sabatier, Anti-personnel mine detection using acoustic to seismic coupling, Proc SPIE vol 4394, pp. 535-542.
2 G.D. Larson, J.S. Martin, W.R. Scott Jr, G.S. McCall II, Environmental Factors that impact the performance of a Seismic Land Mine Detection System, SPIE vol 4394, pp. 563-574.
3 W.R. Scott Jr, S.H. Lee, G.D. Larson, J.S. Martin, G.S. McCall II, Use of High-Frequency Seismic Waves for the Detection of Buried Land Mines, SPIE vol 4394, pp. 543-552.
4 R.D. Costley, J.M. Sabatier, N. Xiang, Forward-looking acoustic mine detection system, SPIE vol 4394, pp.617-626.

5 S. Sen, M. Manciu, K. Campbell, J. Schein, R.R. Prasad and M. Krishnan, Impulse Backscattering Based Detection and Imaging of BuriedObjects in Ganular Beds, SPIE vol 4394, pp.607-616.
6 D. Velea, C. Hickey, J.M. Sabatier, Acoustic scattering by buried objects in a rigid porous material, SPIE vol 4394, pp.595-606.
7 D. Donskoy, N. Sedunov, A. Ekimov, M. Tsionskiy, Optimization of seimo-acoustic land mine detection using dynamic mechanical impedances of mines and soil, SPIE vol 4394, pp.575-582.
8 S.W. McKnight, J. Stott, C.A. DiMarzio, R Cleveland, R. Roy, Laser-induced acoustic imaging of buried land mines: experiment and modeling, SPIE vol 4394, pp. 627-633.
9 Y.Q. Zeng, Q.H. Liu, Acoustic landmine detection: a 3D poroelastic model, SPIE vol 4394, pp. 583-594.
10 C. T Schröder, W.R. Scott Jr, Resonace Behavior of Buried Land Mines, SPIE vol 4394, pp. 553-562.
11 D.M. Donskoy, Detection and discrimination of nonmetallic land mines, SPIE vol 3710, April 1999.

Abstract 1 3pSP1. Using acoustic impulses to detect buried objects.
Charles G. Don, David E. Lawrence, and Andrew J. Rogers Dept. of Phys., Monash Univ., Vic 3168, Australia
A detector of nonmetallic buried objects, such as land mines, has been developed using acoustic impulses with a peak energy around 1 kHz. The initial proposal was to compare the difference in signals from two microphones spaced equally on either side of the sound source held a few centimeters above the ground. Ideally, over a uniform surface the difference signal is zero, however, when one microphone is over an object an additional reflected pulse remains after subtraction. In practice, this pulse is small and often obscured by noise. Better results have been obtained if data from a single microphone is subtracted from a ''reference'' wave-form. Some problems which have to be overcome are optimizing the alignment of the two pulse trains and deciding whether or not to normalize the signals prior to subtraction. If care is not exercised, either process may distort or mask the required object reflection. This small reflected signal can be further enhanced, compared to the background noise, by correlating with an appropriate known waveform. Mention will also be made of the effects of different media and surface contours with the published results. The effects of the finite gain and band-width of the real operational amplifier have also been investigated. The proposed new equalizer shows to be robust against these amplifier imperfections.

4pPA1. Systematic investigation on acoustic-to-seismic responses of landmines buried in soil. James M. Sabatier and Ning Xiang Natl. Ctr. for Physical Acoust., Coliseum Dr., Univ. of Mississippi, University, MS 38677, sabatier@olemiss.edu!
Recently, acoustic-to-seismic coupling has been successfully applied to landmine detection Sabatier and Xiang, J. Acoust. Soc. Am. **105**, 1383; **106**, 2143. When airborne sound penetrates the surface of ground it is refracted towards the normal. If a landmine is buried below the surface of an insonified patch, the transmitted waves will be scattered or reflected, resulting in increased ground surface vibrational amplitudes. These distinct acoustic-to-seismic coupled vibrational changes are sensed using a scanning laser Doppler-vibrometer LDV device. To better under-stand this mine detection phenomenon, the present work is a systematic investigation of the acoustic-to-seismic response to different types of mines in different soil types and at different burial

depth has been conducted. This work is supported by U.S. Army Communications-Electronics Command.

4pPA2. Air acoustic sensing of seismic waves. Gregg D. Larson, James S. Martin School of Mech. Eng., Georgia Inst. of Technol., Atlanta, GA 30332-040, Waymond R. Scott, Jr., and Cheng Jia, Georgia Inst. Of Technol., Atlanta, GA 30332.
Propagation of elastic waves in damp, compacted sand involves pressure, shear, and Rayleigh waves. The associated seismic surface displacements can be detected by sensing the acoustic pressure immediately above the surface. Propagation speeds are very low in sand. The high wave numbers of seismic displacements are, therefore, evanescent in air. Thus, the acoustic pressure can only be measured well within a seismic wave-length of the surface. Planar near-field acoustic holography techniques can then be used to back-propagate these signals and calculate surface displacements. Measurements have been made using a laboratory experimental model to investigate the potential of using this technique to detect buried land mines. The experimental model utilizes a surface-coupled transducer to generate elastic waves in a sand-filled tank, which simulates the earth. The microphone and a radar system were used to independently measure the surface displacements. Data taken with both sensors compare well and exhibit the signature of a buried inert antipersonnel mine. For a 100–800-Hz incident pulse, the mine signature can be seen in the raw microphone data when the height of the microphone is less than 3 cm. Holographic signal-processing techniques will be investigated to increase the allowable height for the microphone. Work supported by ARO.

5pPAc2. Physics of acoustic-to-seismic coupling and detection of buried objects. James M. Sabatier and Ning Xiang Natl. Ctr. For Physical Acoust., Univ. of Mississippi, University, MS 38677, sabatier@olemiss.edu
Airborne acoustic waves coupled into the surface of the ground excite Biot type I and II compressional and shear waves. If a mine-like target or other inhomogeneity is present below the surface, the ground surface vibrational velocity will show distinct changes due to reflection and scattering of these waves. Sound waves with a wavelength comparable to the object size are suitable for recognizing geometrical shapes of targets, while true wave-like acoustic scattering phenomena can be observed with a shorter acoustic wavelength. In this paper, a review of porous material physics relevant to mine detection will be presented. Recent development in the acoustic technology for mine detection will be reported. Taking advantage of a noncontact measurement technique, the surface vibrational velocity is detected with a laser Doppler vibrometer. This work is supported by U.S. Army Communications-Electronics Command.

2aPA2. Acoustic landmine detection using laser scanning vibrometer.
James Sabatier and Ning Xiang, Natl. Ctr. for Physical Acoust., Univ. of Mississippi, University, MS 38677.
Airborne acoustic waves that couple into the surface of the ground excite Biot compressional and shear waves. If a minelike target is present below the surface, the ground surface vibrational velocity will show dis-tinct changes due to reflection and scattering of these waves. Taking ad-vantage of a noncontact measurement technique, the surface vibrational velocity is detected with a laser Doppler vibrometer. Sound waves with a wavelength comparable to the object size are suitable for recognizing geo-metrical shapes of targets, while true wavelike acoustic scattering phenomena can be observed with a shorter acoustic wavelength. In the present contribution, both shape/size recognition and scattering phenomena of buried mines detected by the laser

Doppler based acoustic detection will be visualized in terms of a number of 2-D and 3-D animations. The work is supported by U. S. Army Communications-Electronics Command.

3 Comparison Acoustic and Laser excitation

The two methods for generating an excitation of the air in the soil: acoustic excitation and laser excitation differ considerably, which leads to a difference in potential operational use. Acoustic excitation is potentially useful for verification purposes since it is a slow but accurate technique, while laser excitation is potentially useful in a detection sensor suite due to in potentially higher speed of operation.
Figure 3.1 shows the principle of the two methods. Acoustic excitation measures the frequency response of the soil while laser excitation measures the pulse response. Both techniques scan the laser probe beam (LDV) across the surface to compose an image of the surface. Since the loudspeaker has to scan the frequency range the method is more time consuming than the laser excitation method, in principle.

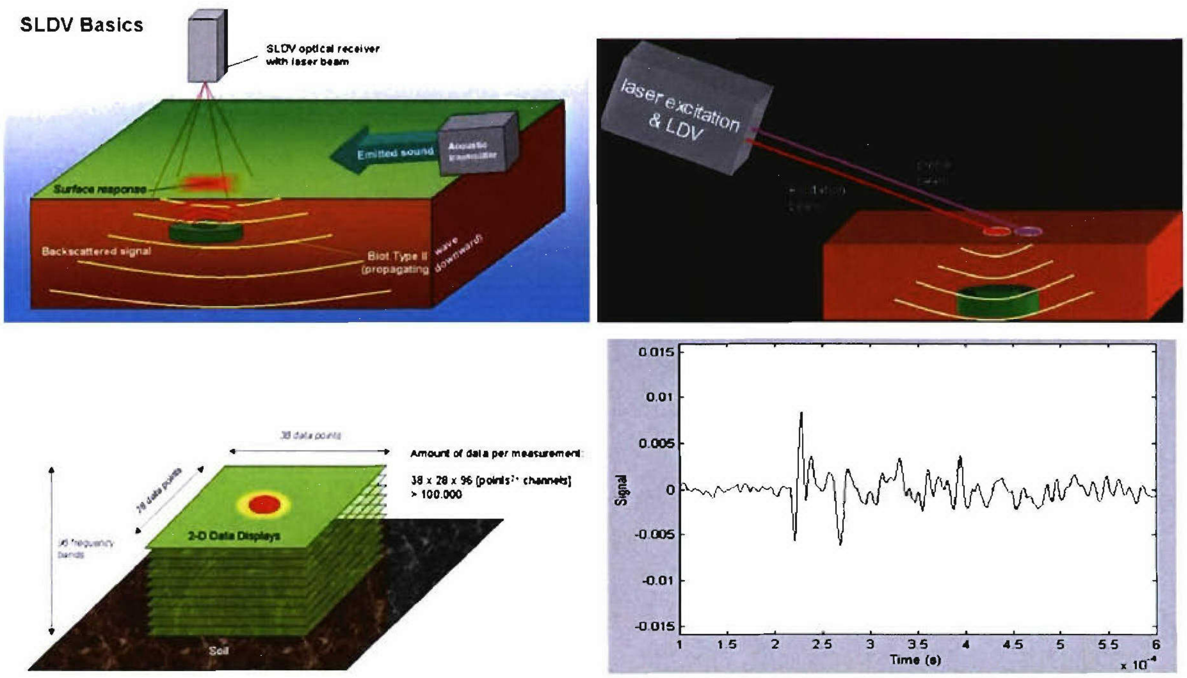


Figure 3.1: Principle of acoustic excitation (left) and laser excitation (right).

Acoustic excitation has been studied by more research groups than laser excitation, as the previous chapter shows. In this chapter we will give a brief overview of the acoustic excitation method based on the combined Netherlands-German field trial of September 2002. Remarks are made on the comparative merits of acoustic excitation versus laser excitation. The content of sections 3.1 and 3.2 was drawn from the SPIE paper:

- J.C. van den Heuvel, V.Klein, P. Lutzmann, F.J.M. van Putten, M. Hebel, and H.M.A. Schleijpen, "Sound wave and laser excitation for acousto-optical landmine detection", in Proc. SPIE, Detection and Remediation Technologies for Mines and Minelike Targets VIII, Orlando (FL), USA, April 2003.

In section 3.3 a concept of a potentially fast system is presented. At present there has been no proof-of-principle study of this concept.

3.1 Overview of acoustic excitation

With the Scanning Laser Doppler Vibrometer (SLDV) technique, an acoustic source – e.g. a loudspeaker – is emitting its acoustic energy towards the ground (left side Figure 3.1). The SLDV instrument is investigating the surface of the ground from a typical distance of some 100 cm (may vary due to operational constraints). The sound source, mostly directly placed on the ground under a slight angle to it, excites slow speed vibrational Biot waves propagating downwards into the soil. These waves are characterized by strong attenuation (typical penetration depth 20-30 cm) and high dispersion. In case a mine or other inhomogeneity is present below the soil surface the transmitted sound waves are scattered or reflected by the buried object. For targets very close to the surface, the scattered field is even indicating shape and size of the buried object. These surface vibration images are read out by the SLDV sensor, scanning the ground in a pre-programmed pattern. Upon completion of a sounding, the SLDV instrument is providing a data set whose structure can be described as 3-dimensional. This data set is depicted in the bottom left part of Figure 3.1. Two-dimensional position data is combined with a third frequency dimension to provide a 3D data set.

Figure 3.2 shows the experimental setup of the acoustic excitation at the outdoor test lanes. The SLDV is a commercial device from the company of POLYTEC with a He-Ne laser source (632 nm). The key issue was the strong shielding for minimizing the impact of the external vibrations on the SLDV. A hi-fi loudspeaker was used for generating the sound (at about 105 dB (0 dB=20μPa) sound pressure level). The composition of this sound spectrum is determined by the spectral data that will be used during the sounding. All frequencies related to the different chosen frequency bands are feeded simultaneously in time (frequency comb) into the loudspeaker. Typical values are covering the spectrum from 40 Hz through 1 kHz.

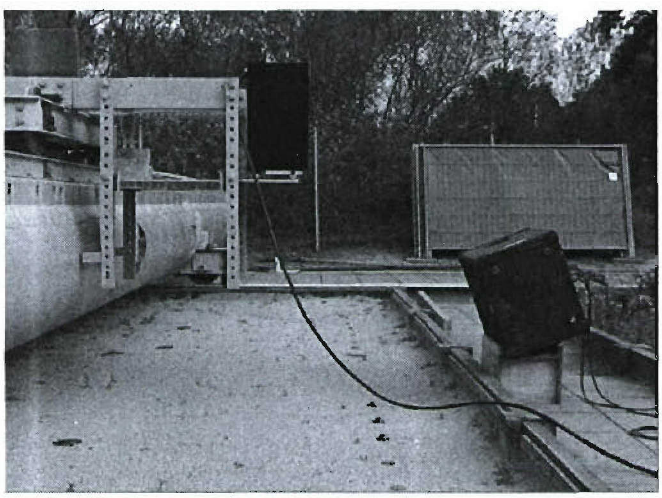


Figure 3.2: Experimental setup of the acoustic excitation at outdoor test lanes.

The recorded vibration images and frequency spectra are characteristic for the type of mine (and different for other buried objects such as stones). The SLDV technique is detecting metal mines as well as plastic mines (e.g. anti-personnel), since it is absolutely independent from any metal content within a mine.

In several successful field trials, different mines and other objects were investigated under the influence of different types of soils (river gravel, loam, clay, sand or grass).

During these field trials, situations with wet or moist soil conditions were encountered, situations that are less favourable for SLDV.

One current drawback is the measurement time needed. A typical multispectral scan of 1 m^2 takes about 8 minutes (38x28 number of points), depending on the selected spatial resolution; but improvements are already being investigated using detector arrays or dedicated predefined acoustic frequencies.

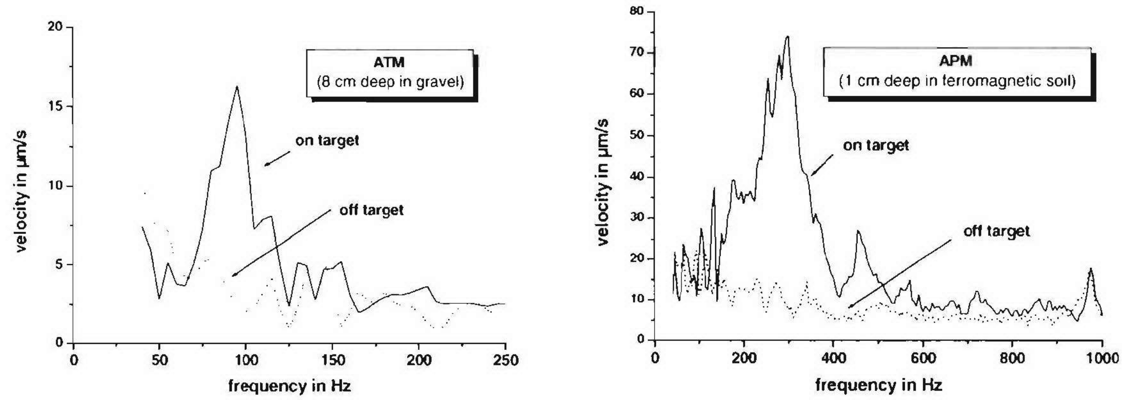


Figure 3.3: Spectral responses directly above the top of the ATM (8 cm deep in gravel) and the APM (1 cm deep in ferromagnetic soil) and besides the mines (off target / background). Note the different main frequency peaks of the two types of mines (ATM at 95 Hz and APM at 295 Hz). Spectral resolution: 5 Hz. The measurements were done with the He-Ne SLDV.

Figure 3.3 reveals an illustrative plot of the velocity in frequency domain of two sampled locations (above the top of the mines and besides the objects). This shows the capability of such a SLDV system. SLDV soundings are clearly indicating an inverse correlation between size and spectral surface responds; smaller objects are scattering higher frequencies, whereas larger objects tend to enhance lower frequencies. The heavier ATM shows a lower frequency response (main frequency peak at 95 Hz) compared to the lighter APM (main frequency peak at 295 Hz); the reason for that is the mine size but also the internal composition.

A presentation of a set of 2-dimensional intensity coded maps, showing the vibration intensities of the individual measurement points in a dedicated intensity scale, of the same mines are given in Figure 3.4. Special smoothing and filtering can additionally be applied to enhance these visualisations. The maps seen here are presenting data of two frequency bands for the ATM as well for the APM, based on an identical geometrical scale. Besides the different frequency response, information about the size and shape of the buried object were available. Of course, the possible determination of the shape and size are reduced by less resolution of the grid (number of scanning points) and deeper buried objects. Additional, more theoretical work was recently been published by Ning Xiang, et al.6

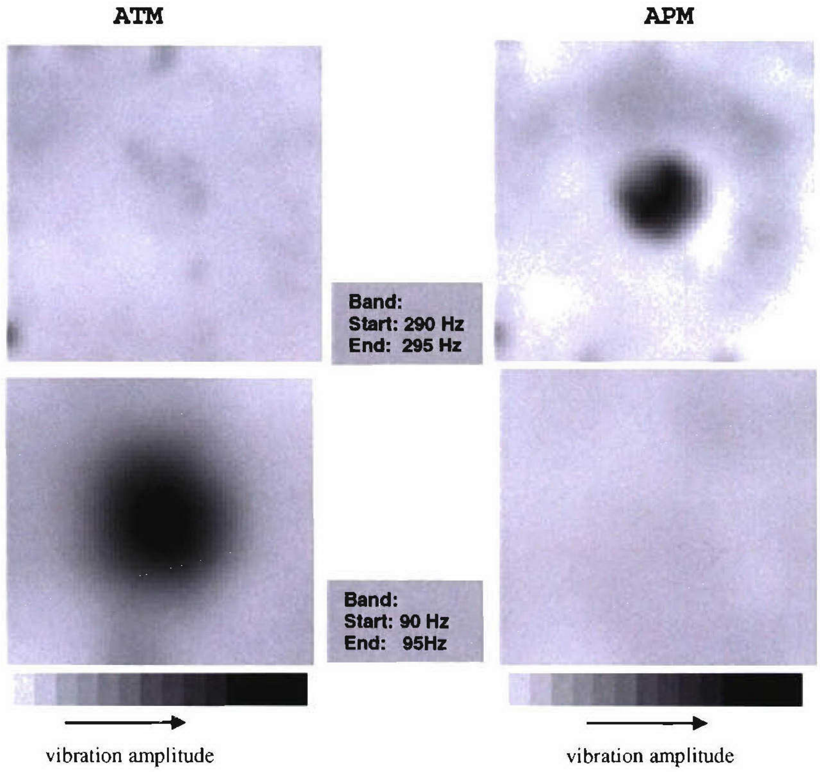


Figure 3.4: SLDV images for two different ranges of vibration frequency and two mine types (anti-tank and anti-personnel). ATM: 8 cm deep in gravel (15x14 points at a scan area of 75x65 cm2) and APM, 1 cm deep in ferromagnetic soil (31x31 points at a scan area of 50x48 cm2). Examining the same scenario at different frequency reveals the type of buried objects at specific frequencies.

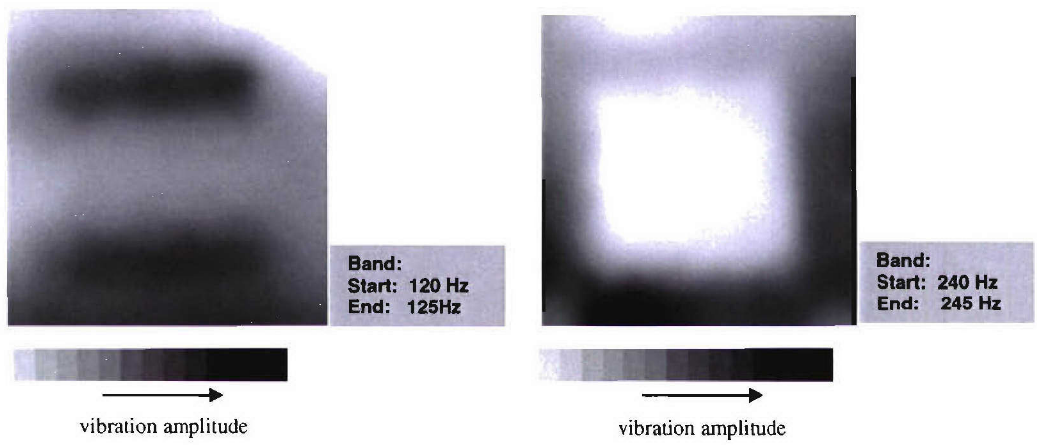


Figure 3.5: Concrete stone (pavement) buried in the sand test bed at 1 cm depth is showing a "negative contrast" at the higher frequency band (lower vibration excursions compared to the surrounding background). At the lower frequency band, only the two opposite edges are showing increased vibration intensities.

Another particular effect is shown by Figure 3.5. Not always an object shaped area of decreased vibration intensity is generated by the underground object. A thick concrete stone (pavement) was buried in the sand test bed at 1 cm depth. Lower vibration signals compared to the surrounding background occurred at certain frequencies. The plate can

clearly been seen at the higher frequency band, but with "negative contrast"; whereas at the lower frequency band, only the two opposite edges are showing increased vibration intensities (the sounding by the loudspeaker was from the lower edge to the upper one).

3.2 Comparison acoustic and laser excitation

The two detection techniques, acoustic excitation (AE) and laser excitation (LE), are not at the same level of technical maturity. The AE technique is much more mature than the LE technique. This is reflected in the almost operational system for AE during the field test and the modified laboratory equipment for the LE.
Both techniques do not depend on metal content for detection and are able to detect buried mines as was shown in the paper. These properties make them valuable for detection of buried land mines. In principle both techniques should be able to detect shape and size of the buried object by scanning the surface. However, in the case of LE this has proven difficult due to the shot-to-shot variations in the acoustic response of the soil. Further analysis of the data is required to assess whether it is possible obtain the shape of the object.
In the 'third' dimension both techniques differ, AE gives the frequency response of the buried object while LE gives the time response. For a first interpretation, the time response gives the depth of the mine, which is convenient for fusion with other sensors that provide depth information. The AE gives the frequency response, which could be used for classification of the buried object (mine). It is conceivable that the time response of the LE could also be used for further classification. However, this has to be shown in a more detailed analysis of the data.
Detection of deep objects seems restricted to AE. The typical results of this paper: 8 cm for AE and 1 cm for LE give a good indication of the difference. It is not expected that LE can detect objects deeper than 3 cm. The excitation energy for LE is much lower compared to AE. In addition, the energy with LE is initiated at a small spot and will disperse over a larger area resulting in a low acoustic response.
Compared to the acoustic excitation, laser excitation is a fast technique. In principle, laser excitation gives a result within a few hundred microseconds, based on the depth of the buried object and the speed of sound in the soil. An operational system could be based on a high rep-rate excitation laser that gives a short pulse every 200 microseconds. With a shot spacing of 1 cm, an area of 100x50 cm could be covered in second. For a vehicle mounted system, this results in an operational speed of 0.5 m/s with a swath width of 1 meter. As has been reported, AE required 8 min for a 1 m^2 area. Thus, LE is, in potential, about two orders of magnitude faster than AE.

3.3 Potentially fast method in acoustic excitation

In the paper listed below a fast laser vibrometry method is described:

- Mauro V. Aguanno, et al, "Full-field laser vibrometry employing a novel CMOS-DSP camera", Proc. SPIE Vol. 4827, p. 123-132, 2002.

The method is based on using a fast CMOS camera for determining the vibration of a surface within the field of view of the camera. Figure 3.6 shows the set-up taken from the paper.

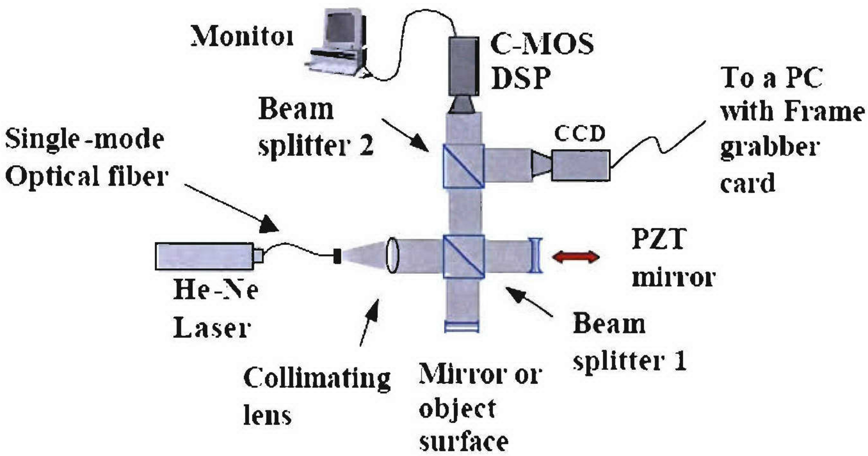


Figure 3.6: The Michelson interferometer set-up with a CMOS camera.

With a high frame-rate CMOS camera it is in principle possible to measure the surface vibration without the use of slow scanners. In the application of ALD it is not a limitation that the wavelength should be below 1 μm in the sensitive range of the CMOS camera. In addition, laser power is too high for the application due to the large range.

In the paper laser vibrometry was only demonstrated on a single pixel of the CMOS camera. The frame-rate of the complete field of view was too low. It remains to be seen whether the required frame-rate can be achieved and whether it can lead to a practical application in ALD.

4 Evaluation Laser excitation

In the previous chapter an overview of the Acoustic Landmine Detection (ALD) with acoustic excitation was given. Furthermore, a comparison with Laser Excitation in ALD was given. In this chapter ALD with laser excitation is treated in more detail. Previous results that are described in the SPIE paper:

- J.C. van den Heuvel, F.J.M. van Putten, A.C. van Koersel, and H.M.A. Schleijpen, "Laser-induced acoustic landmine detection with experimental results on buried landmines", in Proc. SPIE, Detection and Remediation Technologies for Mines and Minelike Targets VIII, Orlando (FL), USA, April 2004.

are summarised below in sections 4.1 and 4.2.

4.1 Acoustical measurements

To attempt to measure the acoustic signal in the ground resulting from experiments with the laser and the loudspeaker, three geophones and three microphones were buried in the sand at different depths. In addition, a fourth microphone was mounted 29 cm above the sand level. Their position and the planned points where the laser was aimed are shown in Figure 4.1. Microphones are B&K ½ inch pre-polarized condenser microphones (type 4129) in connection with a B&K preamplifier, Geophones were vertical type SM-6B of Geosource, they have a coil resistance of 375 Ohm and a natural frequency of 4.5 Hz.

Table 4.1: Sensor Numbering, type, position and sensitivity.

Sensor	Type	Position (x,y,z) in cm	Recorder Bandwidth	Sensitivity
M1	B&K	(0, -10, -2)	20 kHz	-26.2 dB V/PA
M2	B&K	(0, -20, -5)	20 kHz	-26.2 dB V/PA
M3	B&K	(0, -30, -10)	20 kHz	-24.8 dB V/PA
M4	B&K	(0, 0, 29)	20 kHz	-24.8 dB V/PA
G1	SM6B	(0, 10, -2)	10 kHz	28.86 dB/cm/s
G2	SM6B	(0, 20, -5)	10 kHz	28.86 dB/cm/s
G3	SM6B	(0, 30, -10)	10 kHz	28.86 dB/cm/s

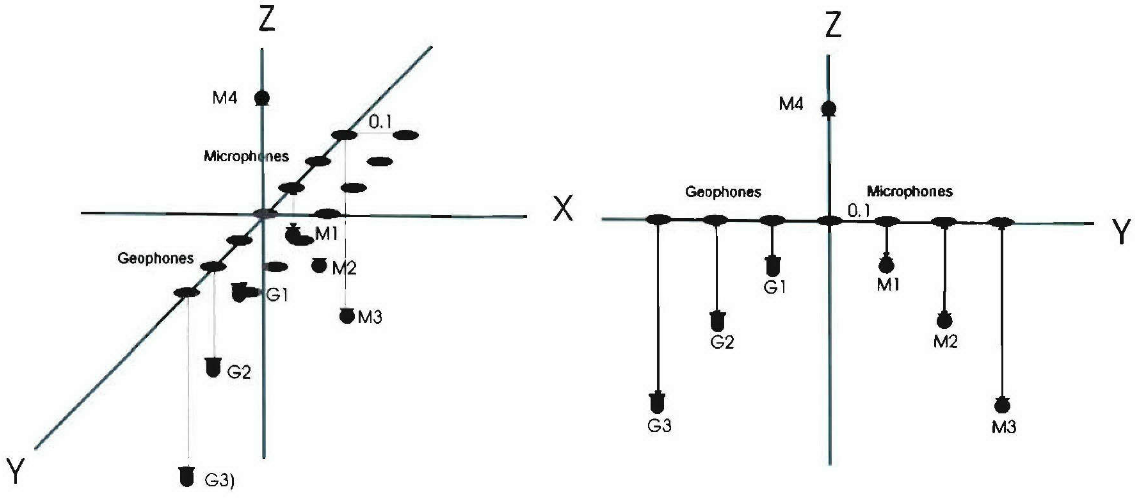


Figure 4.1: Microphone and geophone positions relative to the origin. Laser spots are indicated by ellipses.

The buried microphones are used to measure the acoustic excitation of the soil from the excitation laser. In addition the microphone in air gives information on the acoustic source. Comparison of both microphone signals gives an indication of the coupling of sound into the soil. Figure 4.2 shows the acoustic signals from the microphone in the air above the laser spot and the microphone below the laser spot buried 2 cm in the sand. It is clear that there is an acoustic excitation in the ground, however, the sound pressure is reduced considerably. Furthermore, the high sound frequencies are attenuated strongly in the sand. The delay of the microphone in air is due to the longer distance from the sand surface, i.e. 29 cm versus 2 cm of the buried microphone. This delay between the signals in the air and in the ground is approximately 0.8 ms, which corresponds quite well with the 27 cm path length difference and a sound speed of 340 m/s.

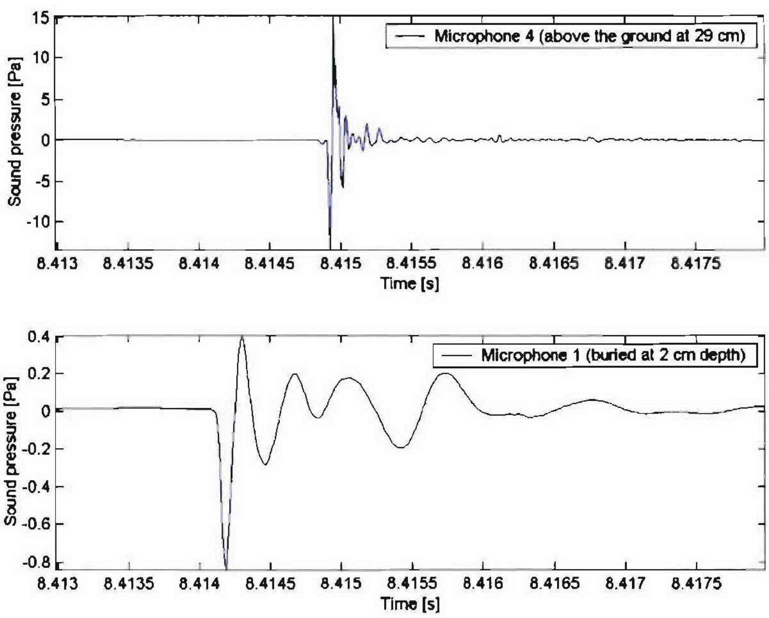


Figure 4.2: Top graph is the microphone in the air, bottom graph is the microphone buried at 2 cm depth. The laser is aimed at a spot on the ground directly above the buried microphone. The graph shows 5 ms of recorded data with one pulse

The shot-to-shot variation of the acoustic signal is quite small. Figure 4.3 shows the acoustic signals of five consecutive laser shots. This means that the excitation of the sand is quite reproducible, which is a requirement for the detection of buried objects by the LDV system.

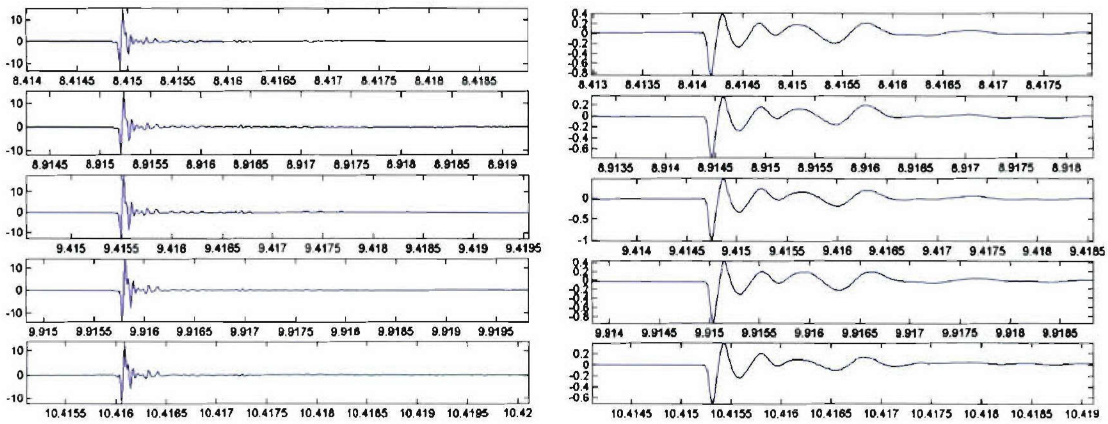


Figure 4.3: Five consecutive acoustic signals of the microphone in air (left) and buried in the sand (right).

Figure 4.4 shows the signals of a buried microphone above a deeper buried landmine. It is clear that there is a difference in the first down peak between the microphone signal above the mine and the microphone signal without a mine. The difference is in the order of 0.1 ms with corresponds to a distance of 3 cm, which is the distance between the mine and the microphone. If an echo from the mine would occur, it would be around 0.2 ms corresponding to twice the distance between the mine and the microphone. It is not clear whether the difference between the signals can be attributed to such an echo.

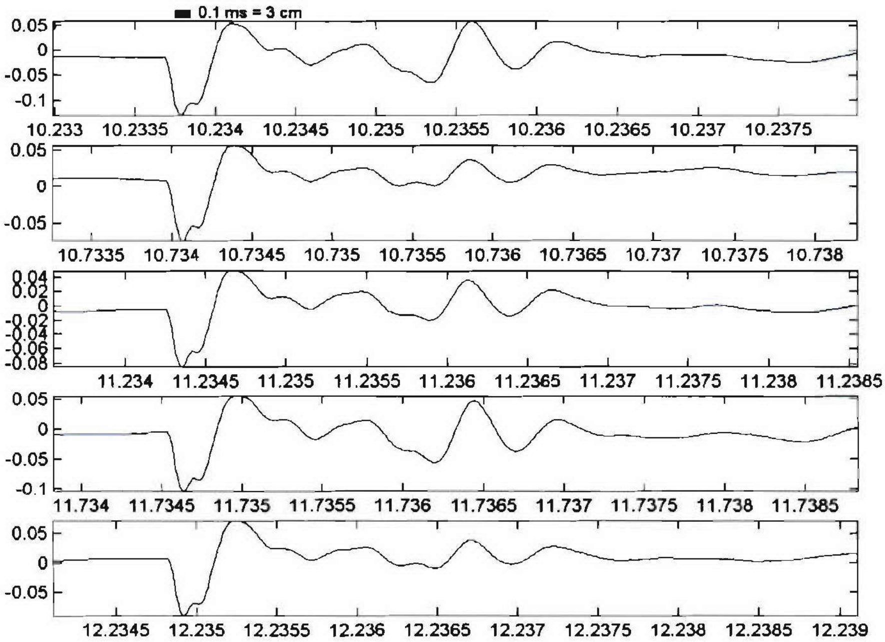


Figure 4.4: Five consecutive acoustic signal of a buried microphone at depth 3 cm above a mine at depth 6 cm. The rectangle at the top indicates 0.1 ms which corresponds to 3 cm depth.

4.2 Laser excitation results

With laser excitation a Q-switched laser pulse heats a small area of the surface of the soil in a very short time of five nanoseconds. Due to the heating of the soil and the secondary heating of the air in and above the soil, an acoustic pulse is generated that propagates in the soil. The vibrations of the soil's surface are measured with an LDV at a range of several meters. These vibrations are modified due to the presence of a buried mine. The detection of the mine is based on the change in surface vibration. In first order the acoustic shock wave generated by the laser pulse reflects back from buried objects to the surface; the echo is measured by the LDV.
The acoustic signal results in a frequency modulation of the 455 kHz high frequency carrier as a result of the Doppler frequency shift $2v/\lambda$, where v is the velocity and λ is the wavelength of the laser. MATLAB was used to demodulate the high frequency signal in order to obtain the instantaneous velocity as a function of time.

The relative position of the excitation laser spot and the monitoring laser spot has to be optimized. If the monitoring laser spot is too close to the excitation spot, the received signal is dominated by scattered soil particles that overwhelm the small response of the buried object. However, if the monitoring laser spot is too far away, the sensitivity for the acoustic signal is too low. In order to find the optimum position, the LDV was pointed at a number of spots at various distances from the excitation spot; distances that were used are between 12 and 24 mm. At every position vibration, data from 16 consecutive pulses was collected by a computer. Figure 4.5 shows the LDV signal when the spots of the two laser beam overlap. The large peaks in the signal are caused by fast moving particles (sand, dust) that are projected from the surface due to the laser excitation.

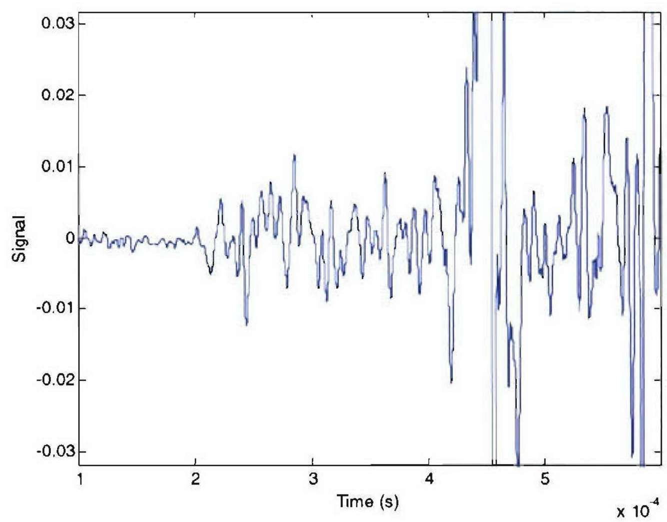


Figure 4.5: Disturbance of the LDV signal by the laser excitation.

For a reliable signal, it is required to separate the two laser spots. Figure 4.6 shows the LDV signal for various separations between probe and excitation laser spots in the situation without a buried object. The first peak is always at the same position and can be attributed to electrical interference of the excitation laser, which was located near the LDV system in these laboratory experiments. In addition, a different excitation laser

was used from that in the field experiment with different electronics for the triggering. For the second peak, it is clear that an increased separation causes an increased delay. This second peak is the acoustic wave that propagates along the surface. Figure 4.7 shows the delay of the LDV signal peak as a function of distance between laser excitation spot and LDV probe spot. The slope of the straight line that connects the points corresponds to a velocity of 340 m/s, which corresponds to the speed of sound.

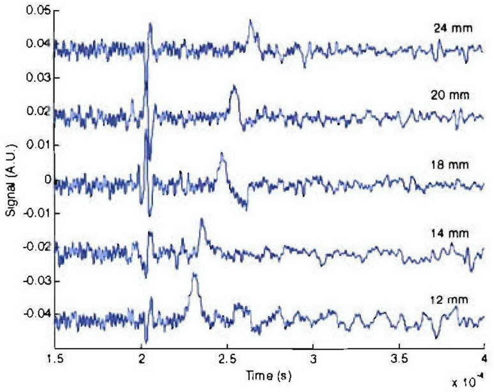


Figure 4.6: LDV signal for various separations between probe and excitation laser spots.

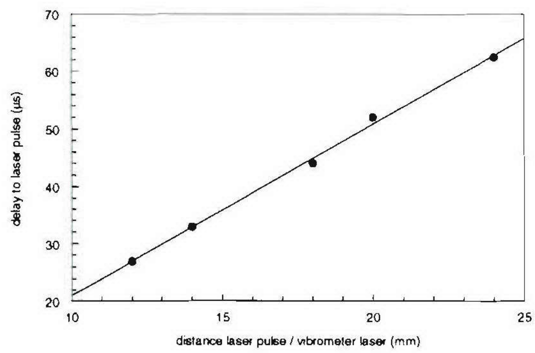


Figure 4.7: Delay of LDV signal as a function of spot separation.

Unfortunately, the shot-to-shot variation of the LDV signal is quite large and increases when a buried object is present. The LDV signals of Figure 4.7 were selected from many shots. Approximately 50% of the shots showed the peak in the LDV at the expected position. The other shots showed large disturbances in the LDV signal.

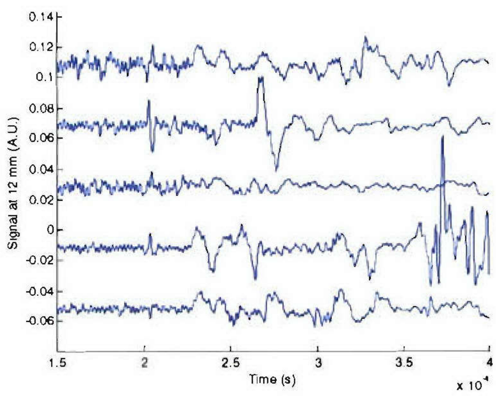


Figure 4.8: Shot-to-shot variation of the LDV signal WITH buried object.

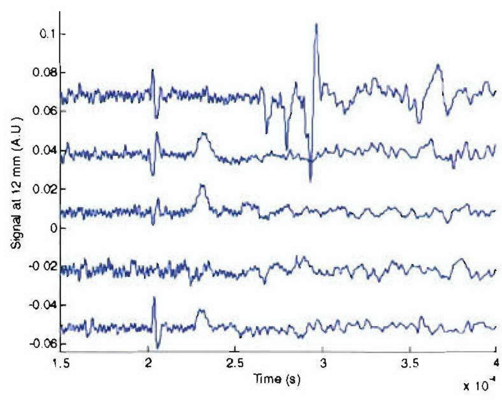


Figure 4.9: Shot-to-shot variation of the LDV signal WITHOUT buried object.

Figure 4.8 and Figure 4.9 show the shot-to-shot variation for the situation with and without a buried object. Both figures show results with the excitation and the probe laser spot at a separation of 12 mm. For some shots with a buried object, it is possible to see a peak at the expected position corresponding to the echo from the buried object. A discussion of these large variations is given in the next section.

The LDV system measures the velocity of the surface at the spot of the probe laser by determining the frequency shift with an FM receiver. Since we know that the Doppler shift is $2v/\lambda$, the signal before FM demodulation is given by

$$s(t) = A(t)\sin\left(2\pi f_C t + 2\pi \frac{2v}{\lambda} t\right) = A(t)\sin\left(2\pi f_C t + 2\pi\phi(t)\right),$$

where A(t) is the amplitude, $\phi(t)$ is the time dependent phase, and fC is the carrier frequency. FM demodulation is the time differentiation of the phase (ignoring the carrier frequency). It is clear from this equation that there is a non-linear relation between two laser-light reflecting points, i.e. the FM demodulation of s1(t)+s2(t) is not the time differentiation of $\phi 1(t)+\phi 2(t)$. This means in practice that areas with different velocities within the laser spot lead to a distorted acoustic signal. Therefore, the laser spot is focused to obtain a clear acoustic signal. However, the consequence is that the LDV signal is very sensitive to local effects and only shows the vibration of a very small surface spot and not the average of the surface vibration as in the microphone experiments that measure pressure variations caused by the entire vibrating surface. Another surface effect that is typical of laser sensing systems is the speckle effect. Due to the high coherence of the laser light the contribution of surface scatterers is added coherently. In imaging systems this leads to granular images, i.e. images with small grains of light and dark spots (speckle). In an LDV system this speckle effect is the cause of extra noise.
Finally, the LDV system is sensitive to fast moving debris from the laser excitation. This effect is absent in microphone measurements.

Detection of the acoustic signal from a buried using an LDV instead of a microphone shows the prospect of stand-off detection using laser excitation for the generation of the acoustic signal and an LDV for detection of the acoustic signature. An additional anticipated advantage of an LDV over a microphone is that an LDV measures the vibration directly at the surface level while the microphone measures in air above the ground. Therefore, the LDV is expected to be more sensitive and to show fewer disturbances from other acoustic noise sources.
However, we have shown that using an LDV gives large shot-to-shot variation, which can be attributed to surface effects. It is not clear how these effects can be reduced in order to make the combination laser excitation and LDV into a reliable system for acoustic landmine detection.

4.3 Acoustic wave propagation in the soil

"Sound" is used for propagating pressure changes or particle movement in gasses, fluids or solids. The general term "Mechanical Waves" is used to distinguish the phenomenon from electromagnetic waves. Acoustic waves occur in fluids and gasses (only longitudinal pressure waves, there are no shear forces in gasses and fluids), seismic waves occur in solids (i.e. soil), where longitudinal (P or pressure) and transversal (S or Shear) waves can occur. The acoustic wave equation is derived from the theorem of conservation of mass for a moving fluid and Euler's equation of motion, with linear approximation. This leads to:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \qquad (1)$$

P is the acoustic pressure in Pa; c represents the speed of the propagating wave in m/s. For an extended treatment of the derivation of the wave equation see i.e. Pierce

[1]. The solution of the three dimensional wave equation is given in equation 2, where s represents an arbitrary source signal:

$$p(r,t) = \frac{s(t - r/c)}{r} \qquad (2)$$

The propagation speed c of the medium is an important parameter, it determines the wavelength for waves of a given frequency that occur in a medium: $\lambda = c/f$. For plane waves in a homogeneous medium the relation between particle velocity v and pressure is given by:

$$v = \frac{\mathbf{n}}{\rho c} p \qquad (3)$$

The term ρc is known as the acoustic impedance of the medium, n is a unit vector. The speed of sound in gasses c is determined from the specific heat ratio, the gas constant and temperature:

$$c = \sqrt{\gamma R T} \qquad (4)$$

For liquids it is obtained from the density ρ and the (adiabatic) bulk modulus K_s:

$$c = \sqrt{K_s / \rho} \qquad (5)$$

For solids the situation is more complicated, since stresses and strains in the material allow the occurrence of transversal waves. According to Berkhout [2] the velocities for propagation of compression (P) waves and transversal (S) waves in homogeneous solids are given by:

$$c_P = \sqrt{\frac{E(1-\sigma)}{(1+\sigma)(1-2\sigma)} \Big/ \rho} \qquad (6)$$

$$c_S = \sqrt{\mu / \rho} \text{ with Lamé constant } \mu = \frac{E}{2(1+\sigma)}$$

E is the modulus of elasticity or Young's modulus (load per unit area divided by the relative elongation), σ is the Poisson ratio (ratio between relative reduction of diameter and relative elongation). Typical values for the speed of compression waves: air 340 m/s, water 1500 m/s, rock 2500 m/s.

The theoretical description of sound propagation in porous media is given by Biot [3,4]. The theory predicts the propagation of two compressional (P) waves (also known als Biot type I and II) and a shear (S) wave. The first compressional wave is characterized by particle motion in phase with the fluid motion, the second compressional wave is characterized by particle motion out of phase with the fluid motion. The second wave has lower speed and higher attenuation. The shear wave has the lowest speed and highest attenuation.

In media like sand stone the compression modulus K can be expressed with a correction term that is related to the porosity according to Geertsma [5].

$$K = 3\frac{1-\sigma}{1+\sigma}K_m + \frac{(1-\beta)^2}{(1-\beta)+(\frac{K_s}{K_f}-1)\phi_0}K_s \quad (7)$$

K_m is the compression modulus of the matrix, K_s of the grain solid, K_f of the fluid, B is the ratio between K_m and K_s, and ϕ_0 is the porosity.

The expressions for pressure waves and shear waves above are derived for *homogeneous* media. In material with boundaries an incident wave of one type will result in transmitted P and S and reflected P and S waves. In addition to the P and S waves there are also waves that occur only on the boundary, Love waves or Q waves are transverse waves that travel along the boundary, Rayleigh waves or R waves are a combination of transverse and compressional waves that rotate along the boundary.

4.3.1 *Seismic Imaging Techniques*

The succesful application of acoustic or seismic imaging techniques depends to a large extent on the degree of contrast (difference in acoustic impedance ρc) between the elastic properties of the surrounding soil and the area of interest, see Heiland [6]. In the case where the distinguishing feature is a slight discoloration of the soil due to the presence of wood that has been consumed long ago by biological processes, the contrast is negligable and therefore the succesfull application of acoustic methods will be equally unlikely. If there is contast between the soil and artefactcs (such as e.g. landmines, waterpipes or other buried objects) it is more likely that acoustic or seismic techniques yield a succesful result.

Seismic imaging techniques are widely used for oil exploration. The techniques are developed to determine the properties of subsurface layers, to identify the location of reservoirs. The group of Acoustic and Seismic technology at the Delft University of Technology performs research on the subject, numerous publications of its former professor Berkhout describe the new techniques for subsurface imaging. Recent publications i.e. are on the topic of Common Focal Point imaging, where the detrimental effects of the so called wheatering layer on reflections of deeper layers are removed using focussing techniques. The conferences organised by EAGE (European Association of Geoscientists & Engineers) or SEG (Society of Exploration Physicists) are platforms where techniques are presented. The articles by Kelamis et al [7] and Hindriks and Verschuur [8] provide insight in recent methods. For the purpose of analysing the surface layer seismic techniques like these are obviously less well suited.

4.3.2 *Measurement techniques used for land mine detection*

There are several techniques for excitation of the soil, and also for the detection of the reflected signals from subsurface objects. These techniques are used in diferent combinations.

- Bottom excitation with loudspeakers transmitting broad band noise, and detection of the scattered sound at the surface using an LDV (Laser Doppler Vibrometer), see Sabatier [10,13,15], detection can also be performed with microphones, Don and Lawrence presented their method at a JASA conference [abstract 1]. Most publications on this method are from Sabatier, from the University of Missisippi. [see abstracts 2, 4, 5] Sabatier works on the subject since 1996, first with a stationary set-up, later with a moving platform using "stop and stare". Modelling of the interaction of mines and the environment is done with a spring-damper model, where the soil over the mine, the mine itself and the soil around the mine have to be

part of the model. The model results in a oscillating behaviour with resonances that are observed in the measured images of the soil. The main part of the response lies between 80 and 300 Hz [Gader, Spie 2002 4742-72].

- Bottom excitation using a laser, and measurement of reflected signals using piezo-electric sensors in the ground, electret microphones close above the ground or laser Doppler vibrometer at a distance, see [McKnight 17]. The article contains the results of measurements in sand. McKnight advises to measure the scattered signal with an LDV, since only part of the energy reflected by objects propagates into the air.
- Bottom excitation using a shaker that generates an elastic surface wave, and measurement of the scattered energy using radar [Scott, 11, 12, 19] and [abstract 3]. Scott presented results at Spie Aerosense 2002, their objective is to use an array of radar sensors to measure bottom vibration. Scott presented results of measurements using two sensors. The design of the antenna has received a lot of attention, a "corrugated horn" is the result. The bottom excitation is done using a seismic shaker that transmits a pulse-like signal (a wavelet). The surface wave (a Rayleigh wave) propagates along the surface, and scatters at buried objects. Scott presented a number of movies with measured signals.
- Donskoy has worked on modelling of the mine-soil system, and presented a new technique at a Spie conference in 1998 [Donskoy 20]. The technique is based on the non-lineairity of the medium, that results in sum and differnce frequencies in the medium if two frequencies are transmitted. This technique is also used in sonar, where it is called parametric sonar. At Spie 2002 new results were presented by Donskoy [4742-77] and Sabatier [4742-79]. The technique is patented (US pt 134.966)

4.3.3 *Measured sound speed and attenuation*

Oelze et al [9] have measured sound speed and attenuation in different soil types. They summarise their findings and explain the observed phenomena in detail. If sound is generated in the air above porous ground (where there is no or little viscous fluid in the pores like dry sand), the sound couples mainly to the air in the pores to produce the slow wave. The slow wave penetrates the soil only to a few centimeters because of its high attenuation and dispersion. According to Sabatier [22] these waves can only be used to image artifacts down to a few centimeters. The high attenuation of the acoustic signals was confirmed by recent measurements at TNO-FEL using a high-power laser as source, and microphones buried in the soil to detect the acoustic signal. The results of these measurements were presented at a SPIE conference in April 2004. An example of a measured signal was given in Figure 4.2.

Note that in the AE experiments in section 3.1 a hi-fi loudspeaker at a sound level of 105 dB is used. The sound level L in dB is the related to the sound pressure by

$$L = 20\log_{10}\left(P / P_0\right) \qquad (8)$$

Where P is the sound pressure and P_0 is 20 μPa. This results in a sound pressure of 3.5 Pa at 105 dB. If we compare this to the sound pressure in Figure 4.2 of the air microphone, we find a comparable pressure level. However, the sound pressure due to the laser excitation lasts only for a fraction of a millisecond. Thus, the acoustic energy in the soil is much lower in the case of laser excitation. In addition the energy is spread over a large frequency range in contrast with the single frequency of the acoustic excitation. It has to be remarked though that the air microphone is located at 29 cm from the ground, so the acoustic energy near the surface will be higher.

There is abundant literature on so called "ground impedance", where models with different numbers of parameters are used to describe the properties of porous media. Attenborough [21] is regarded as the expert in the field with numerous publications on the subject. These publications are often referred to in the field of atmospheric sound propagation, where the reflective properties of the surface are important to calculate long range propagation loss.

Oelze et al states that to image objects at larger depth, the acoustic energy has to be coupled to the frame of the soil itself. Either through direct contact with the soil, or through a layer of fluid or solid material which is closer to the impedance of the solid frame of the soil. Oelze et al measured the attenuation and speed in 6 different soil types, from sand to soil whith higher silt and clay content. The measurements were conducted at two levels of compactness, and different values of water content. They observed lineair dependence with frequency, over a measurement range from 2 kHz to 6 kHz. Attenuation ranges from 0.12 dB/cmkHz to 0.96 dB/cmkHz for different soil types and level of compactness. Observed speed of sound ranges from about 86 m/s to 253 m/s. The higher speeds were observed for the loose, dry soil samples. The high attenuation values were observed for the compact moist samples.

4.3.4 *Resolution versus penetration*

If the obtainable image resolution is approximated with the acoustic wavelength of the signal ($\lambda=c/f$) the soil properties result in a tradeoff between obtainable resolution and penetration depth. If the frequency increases, the resolution increases, and the attenuation is higher resulting in a lower penetration depth of the signal. Oelze et al conclude that for an image resolution of 5 cm, and operating frequency range of 1.7 to 5.2 kHz would be required. Using those frequencies an imaging depth of 30-40 cm would be feasible, given that there is a good impedance match between the source-receiver combination and the soil.

Frazier et al [23] have built an experimental system using a torpedo transducer array as receiver, and a single transducer element as source. The coupling between the soil and the transducer is obtained by using a plastic childs pool filled with a small layer of water. They use a delay and sum beamforming algorithm on the receiver array. In the experimental setup they obtain images from buried objects, in the examples shown in their paper they were buried at approximately 10 cm depth. Frazer et conclude that with synthetic aperture techniques and transducers that are matched to the surface, better results should be possible.

4.3.5 *References*

1 A.D. Pierce, Acoustics, An introduction to its Physical principles and Applications, Acoustical Society of America, Woodbury, New York, 1989.
2 A.J. Berkhout, Seismic Migration, imaging of acoustic energy by wave field extrapolation, A. Theoretical Aspects, Elsevier, Amsterdam, 1982.
3 M.A. Biot, Theory of Propagation of elastic Waves in a Fluid-Saturated Porous Solid, I. Low-Frequency Range, J. Acoust. Soc. Am 28:168-178.
4 M.A. Biot, Theory of Propagation of elastic Waves in a Fluid-Saturated Porous Solid, II. High-Frequency Range, J. Acoust. Soc. Am 28:1179-191.
5 J. Geertsma, Velocity-log Interpretation: The Effect of Rock Bulk Compressibility, J. Soc. Petr. Eng, p 235-248.
6 C.A. Heiland, Geophysical Exploration, Prentice-Hall, New York, 1946.

7 P.G. Kelamis, C.O.H Hindriks, D.J. Verschuur, K.E. Erickson, A.J.W. Duijndam and A.J. Berkhout, The CFP-approach to complex near surface problems, presented at the 62nd EAGE conference, Glasgow, 2000.
8 C.O.H. Hindriks and D.J. Verschuur, Common Focus Point approach to complex near surface effects, Proceedings of the 2001 annual meeting of the SEG, San Antionio Texas, 2001.
9 M.L. Oelze, W.D. O'Brien Jr and R.G. Darmody, Measurement of Attenuation and Speed of Sound in Soils, Soil Sci. Soc. Am. J. 66:788-796 (2002).
10 Ning Xiang and James M. Sabatier, Anti-personnel mine detection using acoustic to seismic coupling, Proc SPIE vol 4394, pp. 535-542.
11 G.D. Larson, J.S. Martin, W.R. Scott Jr, G.S. McCall II, Environmental Factors that impact the performance of a Seismic Land Mine Detection System, SPIE vol 4394, pp. 563-574.
12 W.R. Scott Jr, S.H. Lee, G.D. Larson, J.S. Martin, G.S. McCall II, Use of High-Frequency Seismic Waves for the Detection of Buried Land Mines, SPIE vol 4394, pp. 543-552.
13 R.D. Costley, J.M. Sabatier, N. Xiang, Forward-looking acoustic mine detection system, SPIE vol 4394, pp.617-626.
14 S. Sen, M. Manciu, K. Campbell, J. Schein, R.R. Prasad and M. Krishnan, Impulse Backscattering Based Detection and Imaging of Buried Objects in Granular Beds, SPIE vol 4394, pp.607-616.
15 D. Velea, C. Hickey, J.M. Sabatier, Acoustic scattering by buried objects in a rigid porous material, SPIE vol 4394, pp.595-606.
16 D. Donskoy, N. Sedunov, A. Ekimov, M. Tsionskiy, Optimization of seimo-acoustic land mine detection using dynamic mechanical impedances of mines and soil, SPIE vol 4394, pp.575-582.
17 S.W. McKnight, J. Stott, C.A. DiMarzio, R Cleveland, R. Roy, Laser-induced acoustic imaging of buried land mines: experiment and modeling, SPIE vol 4394, pp. 627-633.
18 Y.Q. Zeng, Q.H. Liu, Acoustic landmine detection: a 3D poroelastic model, SPIE vol 4394, pp. 583-594.
19 C. T Schröder, W.R. Scott Jr, Resonance Behavior of Buried Land Mines, SPIE vol 4394, pp. 553-562.
20 D.M. Donskoy, Detection and discrimination of nonmetallic land mines, SPIE vol 3710, April 1999.
21 Keith Attenborough and Tim Waters Fuller, Effective impedance of rough porous ground surfaces, J. Acoust. Soc. Am. 108(3), pt 1, sep 2000, pp. 949-956.
22 J.M. Sabatier, X. Xing and R. craig, High-resolution velocity images of targets buried in soils, J. Acoust. Soc. Am. 104(1), p. 1783.
23 C.H. Frazier, N. Çadali, D.C. Munson, W.D. O'Brien, Acoustic imaging of objects buries in soil, J. Acoust. Soc. Am. 108 (1), pp. 147-156, July 2000.

4.4 LDV signals at longer timescale

In section 4.2 LDV signals were shown up to 0.4 ms after the laser excitation. In this section we will show the LDV signals up to 4 ms.
It was already mentioned that a severe limitation of the laser excitation method is the shot-to-shot variation that was attributed surface effects. Further analysis of experimental data at longer timescales shows that surface relaxation after the laser excitation can be identified as one of these surface effects.

Figure 4.10 and Figure 4.11 shows the LDV signal for 12 mm and 20 mm separation between the probe laser and the laser excitation. In these figures the LDV signal is plotted at the measured surface speed, since the LDV measures the Doppler frequency shift with can be expressed at the surface speed. Figure 4.10 is identical to Figure 4.8 except for the signal being expressed in surface speed and with slightly lower cut-off frequency (150 versus 200 kHz) in the low-pass filter.

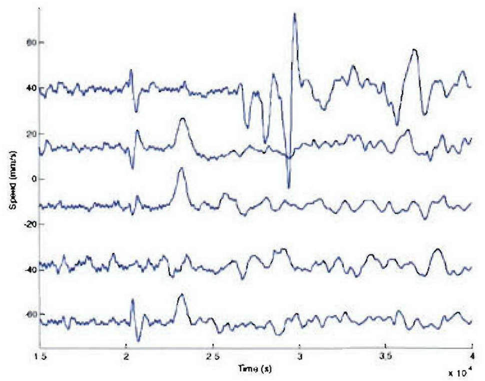


Figure 4.10: Shot-to-shot variation of the LDV signal without buried object with the probe laserspot at **12 mm** from the laser-excitation spot.

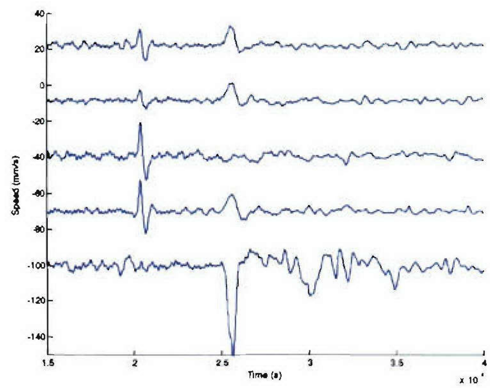


Figure 4.11: Shot-to-shot variation of the LDV signal without buried object with the laserspot at **20 mm** from the laser-excitation spot.

If we compare the two figures above, it is clear that the signal after the surface peak is much lower for the 20 mm probe-excitation separation than for the 12 mm. The surface peak is located around 30 and 50 μs after the excitation pulse and is located at around 250 μs on figures' timescale.

This difference is even clearer if we use a longer timescale and use a low-pass filter, comparable to the acoustical measurements, with a cut-off frequency of 5 kHz. Figure 4.12 and Figure 4.13 show that the signal is much more silent in the case of the longer probe-excitation separation. Even 4 ms after the excitation, there is still a large LDV signal for the 12 mm separation between probe- and excitation-spot. Due to the filtering and the longer timescale, the surface peak is difficult to distinguish from the noise.

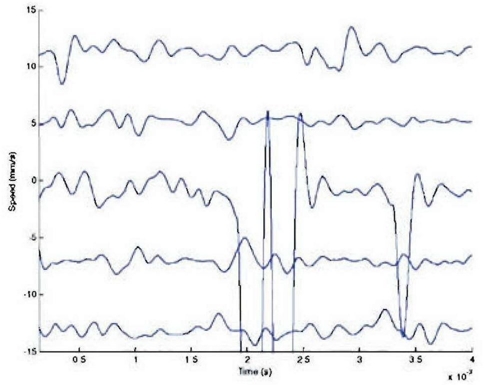


Figure 4.12: LDV signal at longer timescale with the probe laserspot at **12 mm** from the laser-excitation spot.

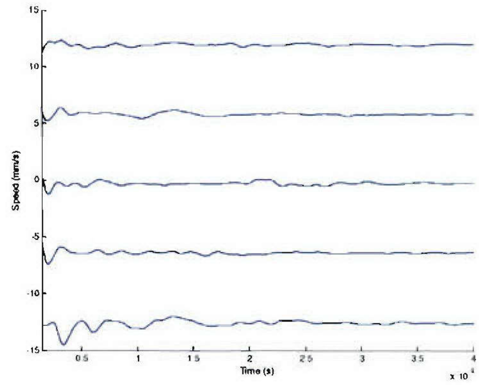


Figure 4.13: LDV signal at longer timescale with the laserspot at **20 mm** from the laser-excitation spot.

A plausible explanation for this effect is surface relaxation. Due to the laser-excitation spot the surface of the soil gets disturbed. In the case of sand a clear depression at the location of the laser spot becomes visible after several shots. It is imaginable that this surface disturbance stretches out a few millimeter outside the perimeter of the laser spot and is relaxed during a few ms.

Figure 4.14 shows the LDV signal on a comparable timescale as the acoustic measurement with a buried microphone. There seems to be a "low" frequency signal in the LDV signals that is similar to the microphone signal, however, no definitive conclusions can be drawn from that. Note that the buried depth of 2 cm for the microphone is similar to the probe-excitation spacing of 20 mm.

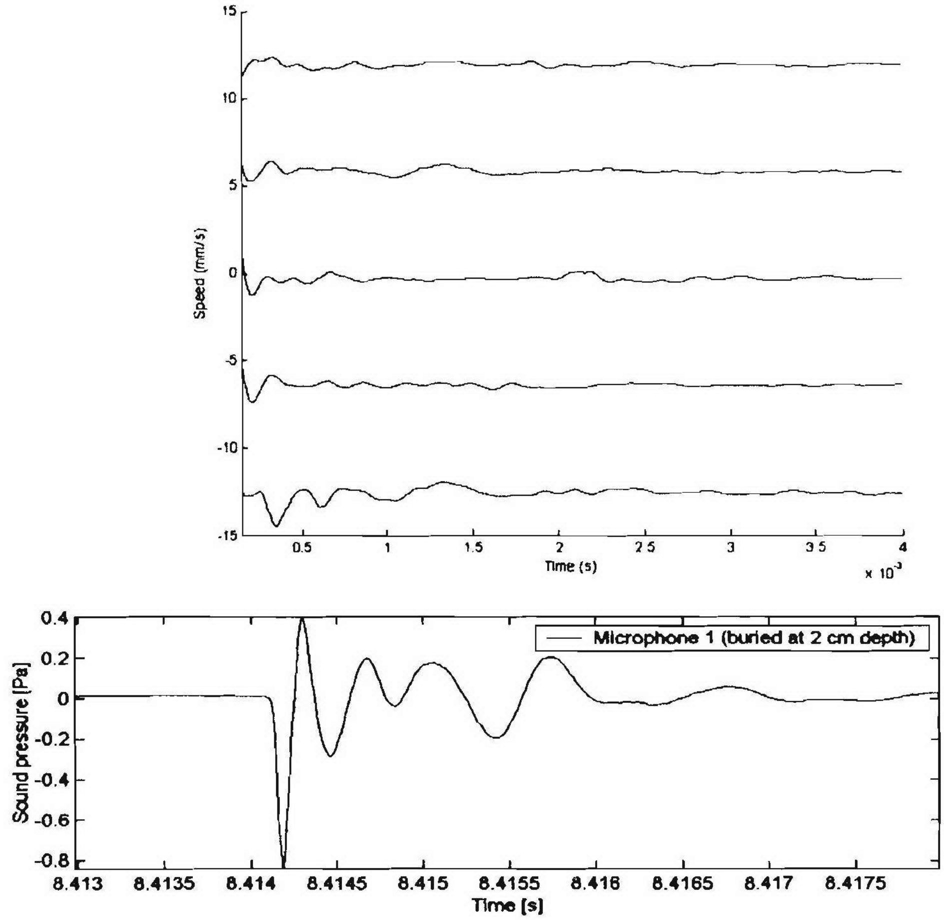


Figure 4.14: LDV signal (top) and buried microphone signal (bottom) on the same timescale.

5 Conclusions

Acoustic landmine detection (ALD) is a promising detection method, since it does not depend on the metal content of landmine. Two ALD excitation methods were studied in this report: acoustic excitation and laser excitation. It was found that acoustic excitation is a valuable technique with good detection properties but is too slow at the moment. The main foreseen use of ALD with acoustic excitation is as an additional verification sensor in a sensor fusion concept due to its low speed. A potentially faster system was proposed here but has not been studied.

ALD with laser excitation has not been studied as extensively as acoustic excitation. Due to the short time-response per excitation pulse, laser excitation could be a fast technique in comparison to acoustic excitation. In addition the laser excitation and the LDV could be located at a certain distance from the mined area, thus providing stand-off detection. However, we have shown that using an LDV in combination with laser excitation gives large shot-to-shot variation obscuring the signal that can be attributed to surface effects. In particular excitation debris (dust particles) and surface relaxation in the vicinity of the laser spot are believed to contribute to this shot-to-shot variation. It is not clear how these effects can be reduced in order to make the combination laser excitation and LDV into a reliable system for acoustic landmine detection.

6 Abbreviations

AE	Acoustic Excitation
ALD	Acoustic Landmine Detection
APM	Anti-Personnel mine
ATM	Anti-Tank mine
FM	Frequency Modulation
GPR	Ground Penetrating Radar
LDV	Laser Doppler Vibrometer
LE	Laser Excitation
SLDV	Scanning LDV
TNO	Netherlands Organisation for Applied Scientific Research

7 Signature

Den Haag, TNO Defensie en Veiligheid

Dr. ir Olijslager
Group leader

Dr. J.C. van den Heuvel
Author

A

This appendix contains a copy of the following paper:

J.C. van den Heuvel, V.Klein, P. Lutzmann, F.J.M. van Putten, M. Hebel, and H.M.A. Schleijpen, "Sound wave and laser excitation for acousto-optical landmine detection", in Proc. SPIE, Detection and Remediation Technologies for Mines and Minelike argets VIII, Orlando (FL), USA, April 2003.

Sound wave and laser excitation for acousto-optical landmine detection

J.C. van den Heuvel[a],V.Klein[b], P. Lutzmann[c], F.J.M. van Putten[a],M. Hebel[c], H.M.A. Schleijpen[a]
[a]TNO Physics and Electronics Laboratory, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands
[b]Kayser-Threde GmbH, Wolfratshauser Str. 48, 81389 Munich, Germany
[c]Forschungsinstitut für Optronik und Mustererkennung (FGAN-FOM), Gutleuthausstrasse 1, 76275 Ettlingen, Germany

ABSTRACT

Acoustic landmine detection (ALD) is a technique for the detection of buried landmines including non-metal mines. An important issue in ALD is the acoustic excitation of the soil. Laser excitation is promising for complete standoff detection using lasers for excitation and monitoring. Acoustic excitation is a more common technique that gives good results but requires an acoustic source close to the measured area. In a field test in 2002 both techniques were compared side by side. A number of buried landmines were measured using both types of excitation. Various types of landmines were used, both anti-tank and anti-personnel, which were buried at various depths in different soil types with varying humidity. Two Laser Doppler Vibrometer (LDV) systems of two different wavelengths for the different approaches were used, one based on a He-Ne laser at 0.633 μm with acoustic excitation and one on an erbium fiber laser at 1.54 μm in the case of laser excitation. The acoustic excitation gives a good contrast between the buried mine and the surrounding soil at certain frequencies. Laser excitation gives a pulse response that is more difficult to interpret but is potentially a faster technique. In both cases buried mines could be detected.

Keywords: landmine detection, buried landmine, non-metal mine, laser Doppler vibrometer

1. INTRODUCTION

Reliable and rapid detection of buried land mines – be it antitank mines (ATM) or antipersonnel mines (APM) – was and is a challenging task for the military as well as the civilian community. In this paper a comparison is made of two acoustic detection techniques: acoustic excitation and laser excitation with a Laser Doppler Vibrometer (LDV) for the detection of surface vibration. Both techniques are valuable in a sensor fusion concept since they provide complementary information about buried objects with respect to GPR or metal detectors.

The acoustic excitation or SLDV (scanning LDV) technique is a promising detection method to contribute to the challenging task of buried land mine detection. However, it has to be stressed that its main use is as an additional verification sensor in a sensor fusion concept. Metal mines as well as plastic mines (e.g. anti-personnel) can be detected, since this approach is absolutely independent from any metal content within a mine. This is valid for a variety of soil types including soils with ferromagnetic content. With ground-penetrating radar, objects embedded in the soil present a dielectric variation and cause a reflection of the electromagnetic wave. This permits a 3D-mapping of the ground, but does not give specific frequency "fingerprints" from objects as does the 2D-mapping by the SLDV with acoustic excitation. The acoustic excitation gives a good contrast between the buried mine and the surrounding soil at certain frequencies. The second technique of laser excitation gives a pulse response that is more difficult to interpret than the acoustic excitation but is potentially a faster technique and besides the shape and size information additional depth information could be detected.

In this paper results of a combined field test of September 2002 are presented. The relative merits of the two techniques are discussed and their potential for use in land mine detection system are assessed.

2. TEST SITE

The experiments have been performed in September 2002 at the test facility for landmine detection systems situated near TNO-FEL.[1] The test facility consists of outdoor test lanes and a sand area that is shielded by a large tent. During these measurements the weather was quite stable without rain and sunny periods.

2.1 Description of the test lanes

The facility consists of six test lanes of 30 square meters each (10x3x1.5m). Four lanes are filled with a native soil with original structure and texture. These soils include sand, clay, peat and a ferromagnetic soil. A fifth lane is filled with a sandy soil with forest remnants like roots and twigs. A sixth lane is filled with a sandy soil but also has a vegetation cover. The soils of the other lanes are bare.

Each type of soil has been characterized. A chemical and physical description is available which gives insight in the texture and structure of the different soil types. The test lanes are completely constructed without the use of electrically conducting material. A zone of 5 meters around the test lanes is cleared from all metal.

A set of test objects, representing anti-personnel mines, anti-tank mines, and false targets (stones, cans, etc.) have been placed at various depths (0-30 cm) in the test lanes. The mines are made of various materials and have different shapes and sizes. Non-metal mines are included.

The test mines have signatures close to those of real mines. To simulate the explosives, the devices have been filled with a silicone rubber. Experiments have proven that this is an excellent surrogate of TNT since both substances have the same electromagnetic and thermal characteristics. In our experiments the vibration issues of the mine surrogates are of crucial importance. Therefore, original mine casings were used for the surrogate mines.

2.2 Description of the shielded sand area

A large tent shields the sand area from rain and wind. It is used for short and flexible tests on landmines in contrast with the test lanes that have mines that have been buried for several years. Mines of identical type as buried in the test lanes were buried in the shielded sand area. Figure 1 shows the mines that were used in the sand area.

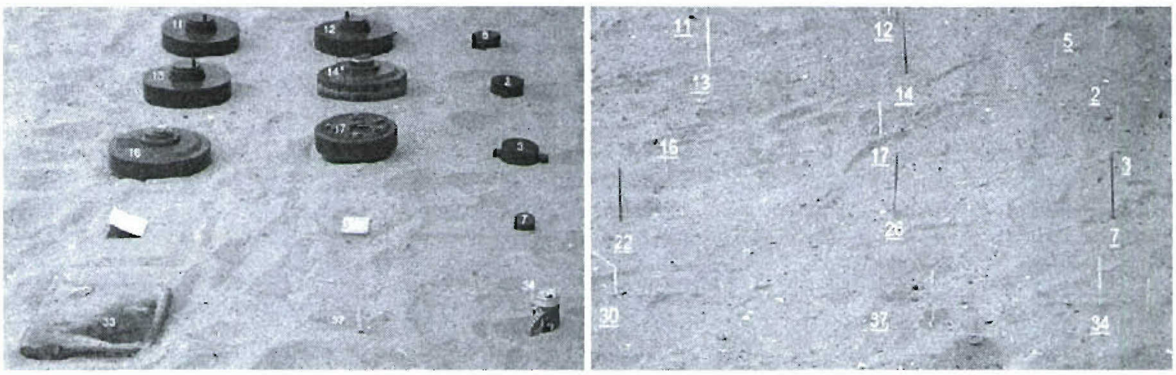


Figure 1: Mines before and after being buried in the sand.

3. ACOUSTIC EXCITATION

3.1 Experimental set-up

With the Scanning Laser Doppler Vibrometer (SLDV) technique, an acoustic source – e.g. a loudspeaker – is emitting its acoustic energy towards the ground (Figure 2). The SLDV instrument is investigating the surface of the ground from a typical distance of some 100 cm (may vary due to operational constraints). The sound source, mostly directly placed on the ground under a slight angle to it, excites slow speed vibrational Biot waves propagating downwards into the soil. These waves are characterized by strong attenuation (typical penetration depth 20-30 cm) and high dispersion. In case a mine or other inhomogeneity is present below the soil surface the transmitted sound waves are scattered or reflected by

the buried object. For targets very close to the surface, the scattered field is even indicating shape and size of the buried object. These surface vibration images are read out by the SLDV sensor, scanning the ground in a pre-programmed pattern. Upon completion of a sounding, the SLDV instrument is providing a data set whose structure can be described as 3-dimensional. This data set is depicted in the right part of Figure 2. Two-dimensional position data is combined with a third frequency dimension to provide a 3D data set.

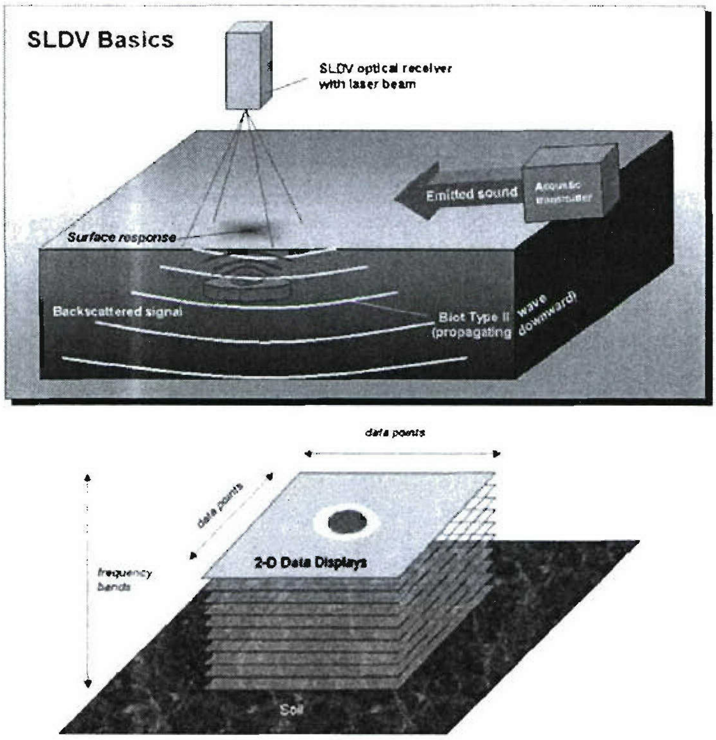


Figure 2: SLDV basics and 3D structure of SLDV data

Figure 3 shows the experimental setup of the acoustic excitation at the outdoor test lanes. The SLDV is a commercial device from the company of POLYTEC with a He-Ne laser source (632 nm). The key issue was the strong shielding for minimizing the impact of the external vibrations on the SLDV. A hi-fi loudspeaker was used for generating the sound (at about 105 dB (0 dB=20μPa) sound pressure level). The composition of this sound spectrum is determined by the spectral data that will be used during the sounding. All frequencies related to the different chosen frequency bands are feeded simultaneously in time (frequency comb) into the loudspeaker. Typical values are covering the spectrum from 40 Hz through 1 kHz.

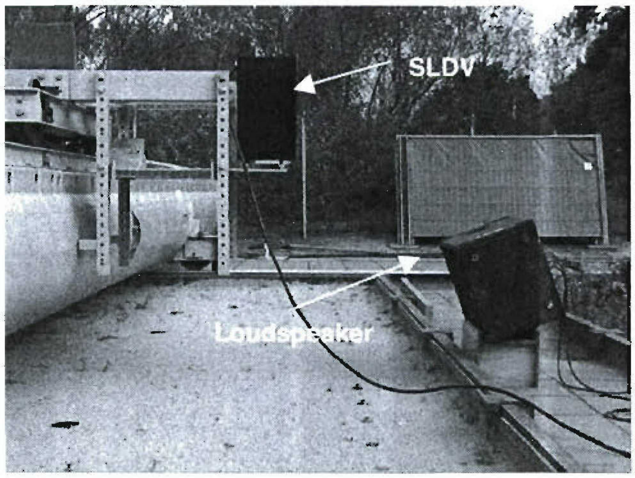


Figure 3: Experimental setup of the acoustic excitation at outdoor test lanes.

3.2 Results

The recorded vibration images and frequency spectra are characteristic for the type of mine (and different for other buried objects such as stones). The SLDV technique is detecting metal mines as well as plastic mines (e.g. anti-personnel), since it is absolutely independent from any metal content within a mine.

In several successful field trials, different mines and other objects were investigated under the influence of different types of soils (river gravel, loam, clay, sand or grass). During these field trials, situations with wet or moist soil conditions were encountered, situations that are less favourable for SLDV.

One current drawback is the measurement time needed. A typical multispectral scan of 1 m^2 takes about 8 minutes (38x28 number of points), depending on the selected spatial resolution; but improvements are already being investigated using detector arrays or dedicated predefined acoustic frequencies.

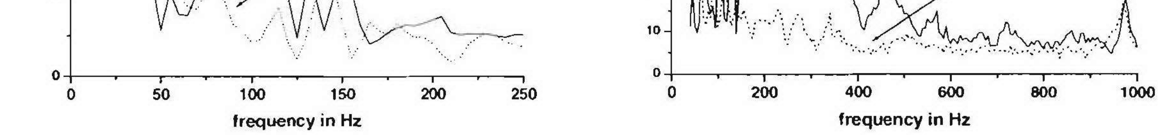


Figure 4: Spectral responses directly above the top of the ATM (8 cm deep in gravel) and the APM (1 cm deep in ferromagnetic soil) and besides the mines (off target / background). Note the different main frequency peaks of the two types of mines (ATM at 95 Hz and APM at 295 Hz). Spectral resolution: 5 Hz. The measurements were done with the He-Ne SLDV.

Figure 4 reveals an illustrative plot of the velocity in frequency domain of two sampled locations (above the top of the mines and besides the objects). This shows the capability of such a SLDV system. SLDV soundings are clearly indicating an inverse correlation between size and spectral surface responds; smaller objects are scattering higher frequencies, whereas larger objects tend to enhance lower frequencies. The heavier ATM shows a lower frequency response (main frequency peak at 95 Hz) compared to the lighter APM (main frequency peak at 295 Hz); the reason for that is the mine size but also the internal composition.

A presentation of a set of 2-dimensional intensity coded maps, showing the vibration intensities of the individual measurement points in a dedicated intensity scale, of the same mines are given in Figure 5. Special smoothing and filtering can additionally be applied to enhance these visualisations. The maps seen here are presenting data of two frequency bands for the ATM as well for the APM, based on an identical geometrical scale. Besides the different frequency response, information about the size and shape of the buried object were available. Of course, the possible determination of the shape and size are reduced by less resolution of the grid (number of scanning points) and deeper buried objects. Additional, more theoretical work was recently been published by Ning Xiang, et al.[6]

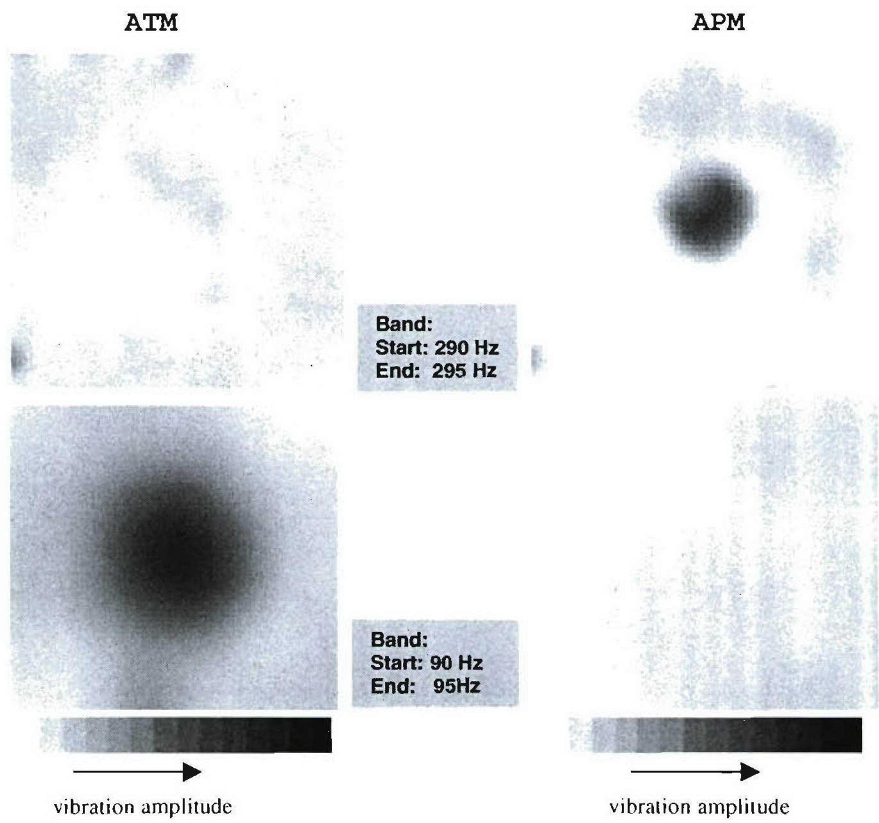


Figure 5: SLDV images for two different ranges of vibration frequency and two mine types (anti-tank and anti-personnel). ATM: 8 cm deep in gravel (15x14 points at a scan area of 75x65 cm^2) and APM, 1 cm deep in ferromagnetic soil (31x31 points at a scan area of 50x48 cm^2). Examining the same scenario at different frequency reveals the type of buried objects at specific frequencies.

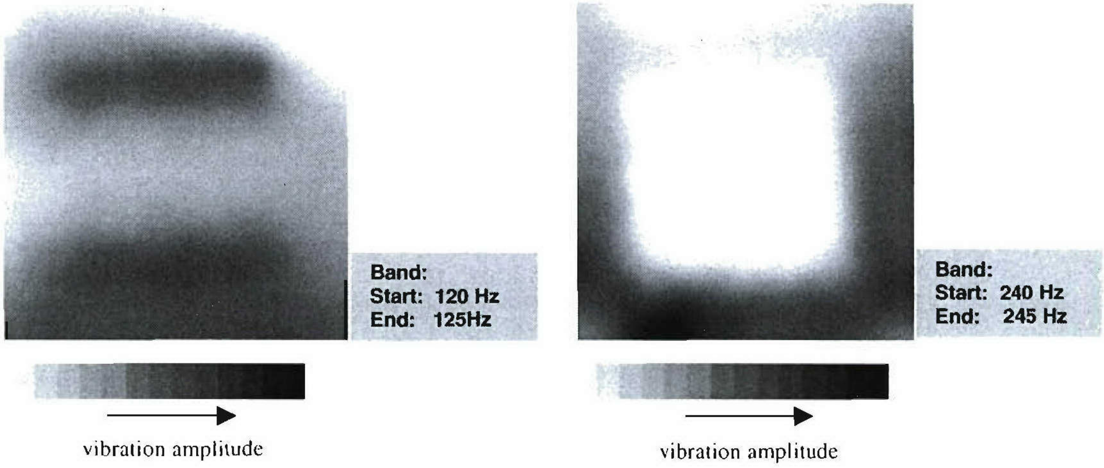


Figure 6: Concrete stone (pavement) buried in the sand test bed at 1 cm depth is showing a "negative contrast" at the higher frequency band (lower vibration excursions compared to the surrounding background). At the lower frequency band, only the two opposite edges are showing increased vibration intensities.

An another particular effect is shown by Figure 6. Not always an object shaped area of decreased vibration intensity is generated by the underground object. A thick concrete stone (pavement) was buried in the sand test bed at 1 cm depth. Lower vibration signals compared to the surrounding background occurred at certain frequencies. The plate can clearly been seen at the higher frequency band, but with "negative contrast"; whereas at the lower frequency band, only the two opposite edges are showing increased vibration intensities (the sounding by the loudspeaker was from the lower edge to the upper one).

4. LASER EXCITATION

4.1 Experimental set-up

Laser excitation is a promising technique for complete standoff detection using lasers for excitation and monitoring. With laser excitation a Q-switched laser pulse heats a small area of the surface of the soil in a very short time of a few nanoseconds. Due to the heating of the soil and the secondary heating of the air in and above the soil, an acoustic pulse is generated that propagates in the soil. The vibrations of the soil's surface are measured with an LDV at a range of several meters. These vibrations are modified due to the presence of a buried mine.[3] The detection of the mine is based on the change in surface vibration. In first order the acoustic shock wave generated by the laser pulse reflects back from buried objects to the surface; the echo is measured by the LDV.

At present we do not use an integrated system but two separate laser systems: one for excitation and one for laser Doppler vibrometry. During research this is not a disadvantage, however, an operational system has to have an integrated excitation laser and monitoring laser. For the excitation of acoustic shock waves a Q-switched Nd:YAG laser was used. This laser (Quantel Brilliant) can deliver pulses with an energy up to 350 mJ with a 20 Hz rep-rate at 1.064 μm (see Figure 7). A variable attenuator and focussing optics resulted in a laser spot of about 1x3 mm on the sand with an energy of 170 mJ.

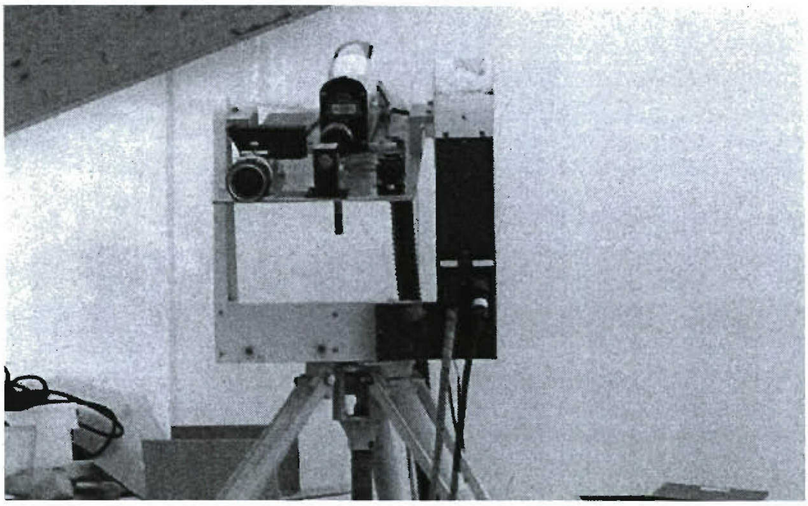


Figure 7: Nd:YAG laser for acoustic excitation.

The laser vibrometer used for the experiments was developed at TNO for long range vibration measurements with a 1 Watt 1542 nm laser source (see Figure 8). Because this high power is not necessary at the short range of a few meters, the power was reduced to about 175 mW.

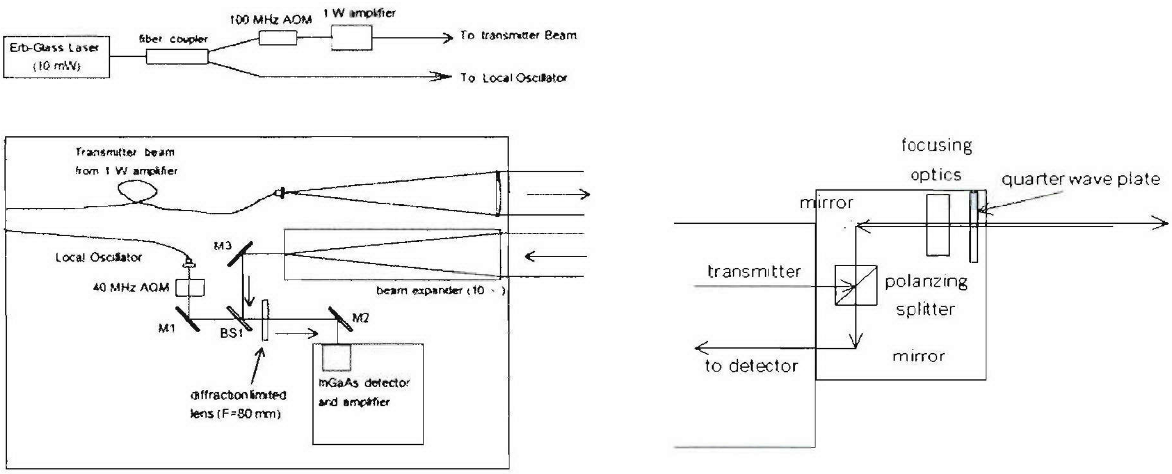


Figure 8: TNO eye-safe laser vibrometer with short range adaptation optics.

Due to the small divergence of the laser and the small field of view of the detector additional optics were placed in front of the system to measure at short distances. Using a polarizing beam-splitter cube and a quarter-wave plate monostatic operation was possible while 2 additional lenses were used to focus at short distances (see fig. Figure 8).
The vibrometer uses 2 Bragg cells (100 MHz and 40 MHz), resulting in a 60 MHz frequency signal at the detector. This signal is mixed down to a frequency of 455 kHz. After amplification the signal is fed to a 10Ms/s AD card and is stored on the computer for further analysis.

The relative position of the excitation laser spot and the monitoring laser spot has to be optimized.[5] If the monitoring laser spot is too close to the excitation spot, the received signal is dominated by scattered soil particles that overwhelm the small response of the buried object. However, if the monitoring laser spot is too far away, the sensitivity for the

acoustic signal is too low. In order to find the optimum position, the LDV was pointed at a number of spots around the spot of the 1.064 μm laser as indicated in Figure 9.

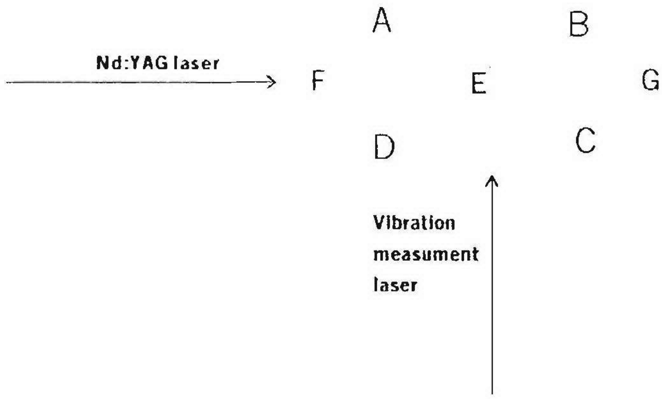


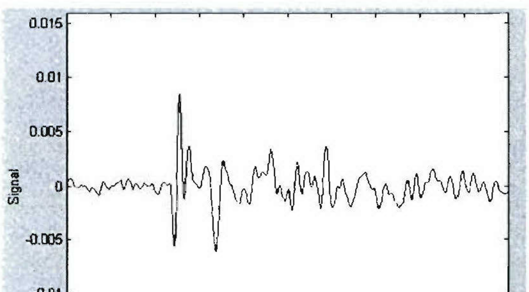
Figure 9: positioning of the laser on the test site

The LDV was aimed at points A to G at about 1 cm from Nd:YAG laser spot E. At every position vibration data from 16 consecutive pulses was collected by a computer.

4.2 Results

The acoustic signal results in a frequency modulation of the 455 kHz high frequency carrier as a result of the Doppler frequency shift $2v/\lambda$, where v is the velocity and λ is the wavelength of the laser. MATLAB was used to demodulate the high frequency signal in order to obtain the instantaneous velocity as a function of time.

The Nd:YAG laser was aimed at the center of mine 11 of which the center was 1 cm deep buried in the sand. Mine 11 is a test mine simulating the anti-tank mine TM62P. As a reference the Nd:YAG laser was also aimed at a position without a buried object. The demodulated signals are shown in Figure 10; the figures on the left and on the right are with and without mine, respectively. About 200 μs after the data acquisition AD card is triggered the laser pulse hits the sand. A clear response is visible due to the surface excitation. Clearly, the LDV measures the acoustic wave created by the laser pulse (first peaks). After about 50 μs another signal is measured as the result of the reflection of the acoustic wave from the mine top.[2] This delay corresponds quite well with the depth of 1 cm and an expected sound velocity of about 340 m/s.[4] If there is no mine beneath the laser spots only the first signal peaks are measured by the LDV.



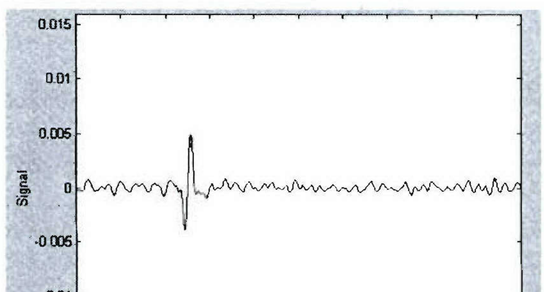


Figure 10: reflected vibration signal from mine 11 (TM62P) at 1 cm depth (left) and signal without mine (right).

The response of the soil shows large variations from shot to shot, both in the first (surface) peak as in the reflection from the test mine. These variations make the interpretation of the data difficult. It is not clear yet whether it is possible to extract more from the data than the approximate depth of a buried object.
It was not possible to detect the presence of an object at a depth of more than 3 cm. However our system has not yet been optimized and further research is required to find the limits of this technique.

5. COMPARISON ACOUSTIC AND LASER EXCITATION

The two detection techniques, acoustic excitation (AE) and laser excitation (LE), are not at the same level of technical maturity. The AE technique is much more mature than the LE technique. This is reflected in the almost operational system for AE during the field test and the modified laboratory equipment for the LE.
Both techniques do not depend on metal content for detection and are able to detect buried mines as was shown in the paper. These properties make them valuable for detection of buried land mines. In principle both techniques should be able to detect shape and size of the buried object by scanning the surface. However, in the case of LE this has proven difficult due to the shot-to-shot variations in the acoustic response of the soil. Further analysis of the data is required to assess whether it is possible obtain the shape of the object.
In the 'third' dimension both techniques differ, AE gives the frequency response of the buried object while LE gives the time response. For a first interpretation, the time response gives the depth of the mine, which is convenient for fusion with other sensors that provide depth information. The AE gives the frequency response, which could be used for classification of the buried object (mine). It is conceivable that the time response of the LE could also be used for further classification. However, this has to be shown in a more detailed analysis of the data.
Detection of deep objects seems restricted to AE. The typical results of this paper: 8 cm for AE and 1 cm for LE give a good indication of the difference. It is not expected that LE can detect objects deeper than 3 cm. The excitation energy for LE is much lower compared to AE. In addition, the energy with LE is initiated at a small spot and will disperse over a larger area resulting in a low acoustic response.
Compared to the acoustic excitation, laser excitation is a fast technique. In principle, laser excitation gives a result within a few hundred microseconds, based on the depth of the buried object and the speed of sound in the soil. An operational system could be based on a high rep-rate excitation laser that gives a short pulse every 200 microseconds. With a shot spacing of 1 cm, an area of 100x50 cm could be covered in second. For a vehicle mounted system, this results in an operational speed of 0.5 m/s with a swath width of 1 meter. As has been reported, AE required 8 min for a 1 m^2 area. Thus, LE is, in potential, about two orders of magnitude faster than AE.

6. CONCLUSIONS

In September 2002 a field test of acoustic land mine detection was performed. Two acousto-optical techniques for the detection of buried landmines have been compared: acoustic excitation and laser excitation of the soil, both with a laser Doppler vibration (LDV) sensor. It has been shown that the techniques are complementary: acoustic excitation is a relatively slow technique that is excellent as a verification sensor, while laser excitation is a fast technique that is much less suited for identifying buried objects. Both techniques have shown promising results in the detection (and classification) of buried mines.
A more detailed analysis of the results of the field test is expected to provide more information on the relative merits of the two techniques. In this subsequent analysis we also plan to use the recorded data of buried microphones. These microphones were used to register the propagation of sound in the soil and provide information on the extinction and the dispersion of the acoustic energy.

REFERENCES

1. W. de Jong, H. A. Lensen, and Y. H. L. Janssen, "Sophisticated test facility to detect land mines," in Proc. SPIE Vol. 3710, Detection and Remediation Technologies for Mines and Minelike Targets IV, A. C. Dubey and J. F. Harvey, eds., pp. 1409–1419, (Orlando (FL), USA), Apr. 1999.

2. W. Li, C.A. DiMarzio and S.W. McKnight, "Laser-induced Acoustic Detection of Shallow-Buried Objects", Proc. SPIE Vol.3752, July 1999.
3. S.W. McKnight et.al., "Laser-induced acoustic generation for buried object detection", Proc. SPIE Vol. 4038 (April 2000).
4. S.W. McKnight, J. Stott, C.A. DiMarzio, R Cleveland, R. Roy, "Laser-induced acoustic imaging of buried land mines: experiment and modeling", SPIE vol 4394, pp. 627-633.
5. Charles A. DiMarzio, et. al., Toward a Laser-Based, "Non-Contact Acoustic Landmine Imager"; Proc. SPIE Vol. 4038 (April 2000)
6. Ning Xiang, "Bayesian Probability Analysis for Acousto-Seismic Landmine Detection", Center for Physical Acoustics, University of Mississippi, Fall meeting of Acoustical Society of America (ASA), Cancun, December 2002

B

This appendix contains a copy of the following paper:

J.C. van den Heuvel, F.J.M. van Putten, A.C. van Koersel, and H.M.A. Schleijpen, "Laser-induced acoustic landmine detection with experimental results on buried landmines", in Proc. SPIE, Detection and Remediation Technologies for Mines and Minelike Targets VIII, Orlando (FL), USA, April 2004.

Laser-induced acoustic landmine detection with experimental results on buried landmines

J.C. van den Heuvel, F.J.M. van Putten, A.C. van Koersel, H.M.A. Schleijpen
TNO Physics and Electronics Laboratory, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands

ABSTRACT

Acoustic landmine detection (ALD) is a technique for the detection of buried landmines including non-metal mines. Since it gives complementary results with GPR or metal detection, sensor fusion of these techniques with acoustic detection would give promising results. Two methods are used for the acoustic excitation of the soil: laser excitation and loudspeaker excitation. A promising concept is using lasers for excitation and monitoring for complete stand-off detection. Results from a field test and laboratory experiments show the feasibility of laser excitation for ALD. In these experiments buried landmine surrogates were measured with ALD using a Nd-YAG laser at 1.06 μm for the acoustic generation and a Laser Doppler Vibrometer (LDV) system at 1.54 μm for the detection of soil vibrations.
An analysis is given of the experimental results showing the potential and the inherent limitations of the technique. We discuss the relative merits of LDV detection versus microphone detection of the laser-induced acoustic vibration. It was found that the LDV has limitations with respect to microphone detection due to the influence of surface effects that are prominent in LDV but absent in microphone detection.

Keywords: landmine detection, buried landmine, non-metal mine, laser Doppler vibrometer

1. INTRODUCTION

Reliable and rapid detection of buried land mines – be it antitank mines (ATM) or antipersonnel mines (APM) – was and is a challenging task for the military as well as the civilian community. In this paper the technique of acoustic landmine detection (ALD) is investigated that uses laser excitation as the acoustic source. Another way of acoustic excitation is by means of a loudspeaker. Both excitation techniques have been compared in ref. [1]. Both techniques are valuable in a sensor fusion concept since they provide complementary information about buried objects with respect to GPR or metal detectors.

The ALD technique is a promising detection method, since it does not depend on the metal content of landmine. Thus, metal mines as well as plastic mines (e.g. anti-personnel) can be detected, since this approach is absolutely independent of any metal content within a mine. This is valid for a variety of soil types including soils with ferromagnetic content.

With ground-penetrating radar, objects embedded in the soil present a dielectric variation and cause a reflection of the electromagnetic wave. This permits a 3D-mapping of the ground, and in principle allows "fingerprinting" the detected object by multiple reflections in the object. Although ALD with loudspeaker excitation allows only 2D-mapping, in allows a similar type of fingerprinting by analysis of the acoustical resonances of the landmine casing. The loudspeaker excitation gives a good contrast between the buried mine and the surrounding soil at certain frequencies. The technique of laser excitation gives a pulse response that is more difficult to interpret than the loudspeaker excitation but is potentially a faster technique and besides the shape and size information additional depth information could be detected. Laser excitation also seems more suitable for remote detection, since the laser energy can easily be pointed 10 or more meters in front of the detection platform.

In this paper results of field tests and laboratory experiments are presented. It is shown that laser excitation gives a reproducible acoustic excitation at the surface and that the acoustic excitation is coupled into the ground. Using the Laser Doppler Vibrometer (LDV) to measure the acoustic signal at the surface, we found a clear signal of the first peak corresponding to the acoustic surface excitation propagating along the surface. However, the LDV signal after the first peak shows large shot-to-shot variation making detection of buried objects difficult. These shot-to-shot variations are

caused by surface effects that are prominent in LDV signals but are negligible in microphone signals. This is a severe limitation in the use of an LDV system in combination with laser excitation for ALD.

2. EXPERIMENTAL SET-UP

2.1 Test site

The experiments were performed in the laboratory and outdoors. The outdoor test consisted of experiments in an outdoor sand area shielded by a large tent. Buried test mines were used. The test mines have signatures close to those of real mines. To simulate the explosives, the devices have been filled with a silicone rubber. Experiments have proven that this is an excellent surrogate of TNT since both substances have the same electromagnetic and thermal characteristics.[2] In our experiments the vibration issues of the mine surrogates are of crucial importance. Therefore, original mine casings and test mine were used in the experiment in order to allows a comparison between the real casings and the test mines. Figure 1 shows the mines that were used in the sand area.

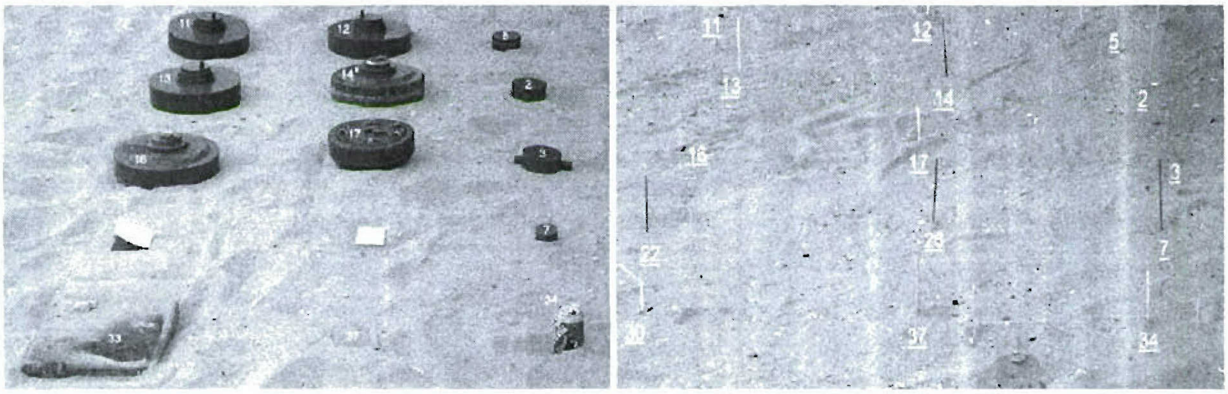


Figure 1: Mines before and after being buried in the sand.

2.2 Microphones and geophones

To attempt to measure the acoustic signal in the ground resulting from experiments with the laser and the loudspeaker, three geophones and three microphones were buried in the sand at different depths. In addition, a fourth microphone was mounted 29 cm above the sand level. Their position and the planned points where the laser was aimed are shown in Figure 2. Microphones are B&K ½ inch pre-polarized condenser microphones (type 4129) in connection with a B&K preamplifier, Geophones were vertical type SM-6B of Geosource, they have a coil resistance of 375 Ohm and a natural frequency of 4.5 Hz.

Table 1: Sensor Numbering, type, position and sensitivity.

Sensor	Type	Position (x,y,z) in cm	Recorder Bandwidth	Sensitivity
M1	B&K	(0, -10, -2)	20 kHz	-26.2 dB V/PA
M2	B&K	(0, -20, -5)	20 kHz	-26.2 dB V/PA
M3	B&K	(0, -30, -10)	20 kHz	-24.8 dB V/PA
M4	B&K	(0, 0, 29)	20 kHz	-24.8 dB V/PA
G1	SM6B	(0, 10, -2)	10 kHz	28.86 dB/cm/s
G2	SM6B	(0, 20, -5)	10 kHz	28.86 dB/cm/s
G3	SM6B	(0, 30, -10)	10 kHz	28.86 dB/cm/s

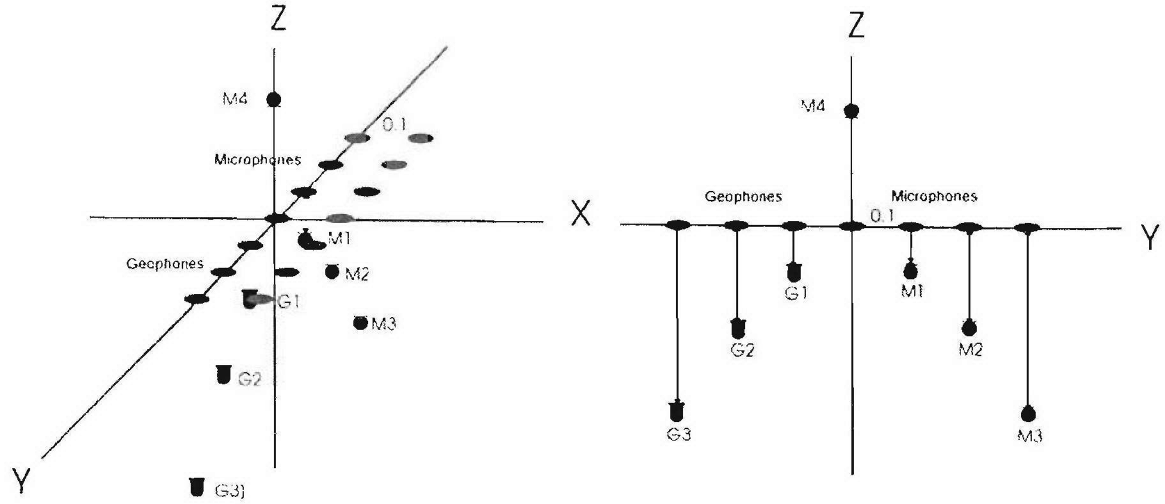


Figure 2: Microphone and geophone positions relative to the origin. Laser spots are indicated by ellipses.

2.3 Laser excitation

With laser excitation a Q-switched laser pulse heats a small area of the surface of the soil in a very short time of five nanoseconds. Due to the heating of the soil and the secondary heating of the air in and above the soil, an acoustic pulse is generated that propagates in the soil. The vibrations of the soil's surface are measured with an LDV at a range of several meters. These vibrations are modified due to the presence of a buried mine.[4] The detection of the mine is based on the change in surface vibration. In first order the acoustic shock wave generated by the laser pulse reflects back from buried objects to the surface; the echo is measured by the LDV.

At present we do not use an integrated system but two separate laser systems: one for excitation and one for laser Doppler vibrometry. During research this is not a disadvantage, however, an operational system has to have an integrated excitation laser and monitoring laser. For the excitation of acoustic shock waves, a Q-switched Nd:YAG laser was used. This laser (Quantel Brilliant) can deliver pulses with an energy up to 350 mJ with a 20 Hz rep-rate at 1.064 μm (see Figure 3). A variable attenuator and focussing optics resulted in a laser spot of about 1x3 mm on the sand with an energy of 170 mJ.

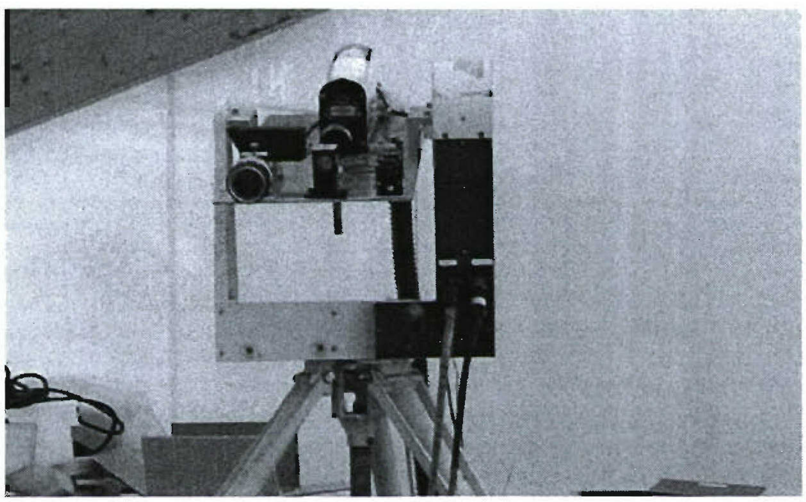


Figure 3: Nd:YAG laser for acoustic excitation.

2.4 Laser Doppler vibrometer

The laser vibrometer used for the experiments was developed at TNO for long range vibration measurements with a 1 Watt 1542 nm laser source (see Figure 4). Because this high power is not necessary at the short range of a few meters, the power was reduced to about 175 mW.

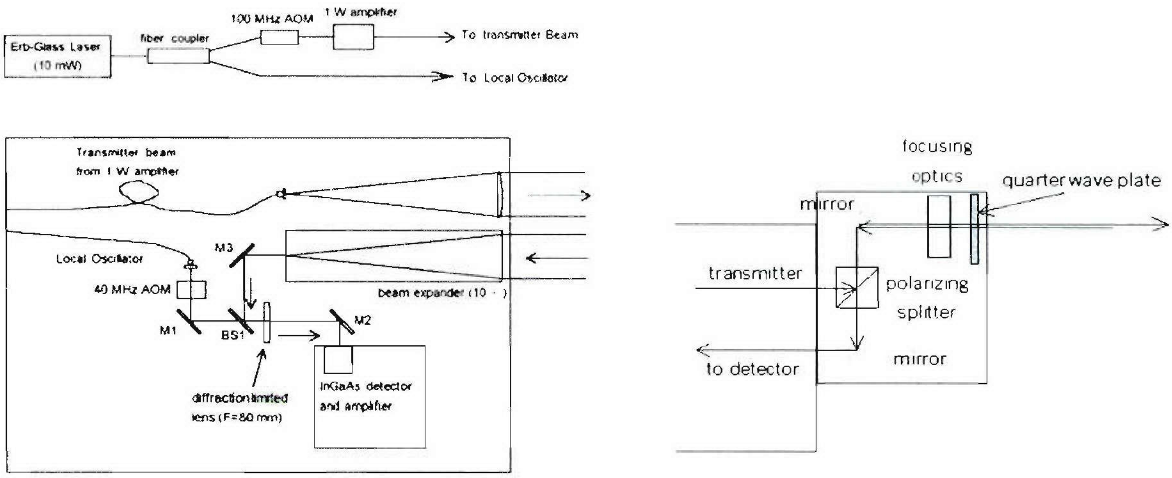


Figure 4: TNO eye-safe laser vibrometer with short range adaptation optics.

Due to the small divergence of the laser and the small field of view of the detector additional optics were placed in front of the system to measure at short distances. Using a polarizing beam-splitter cube and a quarter-wave plate monostatic operation was possible while 2 additional lenses were used to focus at short distances (see fig. Figure 4). The spot size of the laser on the ground was about 1 to 2 mm.
The vibrometer uses 2 Bragg cells (100 MHz and 40 MHz), resulting in a 60 MHz frequency signal at the detector. This signal is mixed down to a frequency of 455 kHz. After amplification the signal is fed to a 10Ms/s AD card and is stored on the computer for further analysis.

The relative position of the excitation laser spot and the monitoring laser spot has to be optimized.[6] If the monitoring laser spot is too close to the excitation spot, the received signal is dominated by scattered soil particles that overwhelm the small response of the buried object. However, if the monitoring laser spot is too far away, the sensitivity for the acoustic signal is too low. In order to find the optimum position, the LDV was pointed at a number of spots at various distances from the excitation spot; distances that were used are between 12 and 24 mm. At every position vibration, data from 16 consecutive pulses was collected by a computer.

3. RESULTS

3.1 Excitation of the soil

The buried microphones are used to measure the acoustic excitation of the soil from the excitation laser. In addition the microphone in air gives information on the acoustic source. Comparison of both microphone signals gives an indication of the coupling of sound into the soil. Figure 5 shows the acoustic signals from the microphone in the air above the laser spot and the microphone below the laser spot buried 2 cm in the sand. It is clear that there is an acoustic excitation in the ground, however, the sound pressure is reduced considerably. Furthermore, the high sound frequencies are attenuated strongly in the sand. The delay of the microphone in air is due to the longer distance from the sand surface, i.e. 29 cm versus 2 cm of the buried microphone. This delay between the signals in the air and in the ground is approximately 0.8 ms, which corresponds quite well with the 27 cm path length difference and a sound speed of 340 m/s.

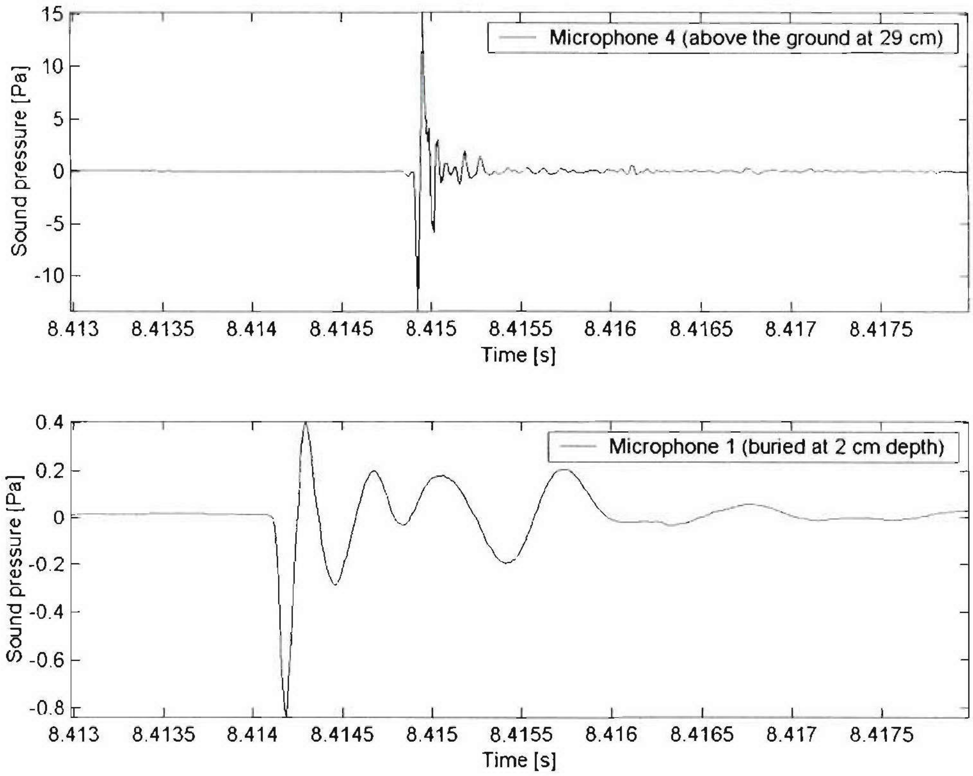


Figure 5: Top graph is the microphone in the air, bottom graph is the microphone buried at 2 cm depth. The laser is aimed at a spot on the ground directly above the buried microphone. The graph shows 5 ms of recorded data with one pulse

The shot-to-shot variation of the acoustic signal is quite small. Figure 6 shows the acoustic signals of five consecutive laser shots. This means that the excitation of the sand is quite reproducible, which is a requirement for the detection of buried objects by the LDV system.

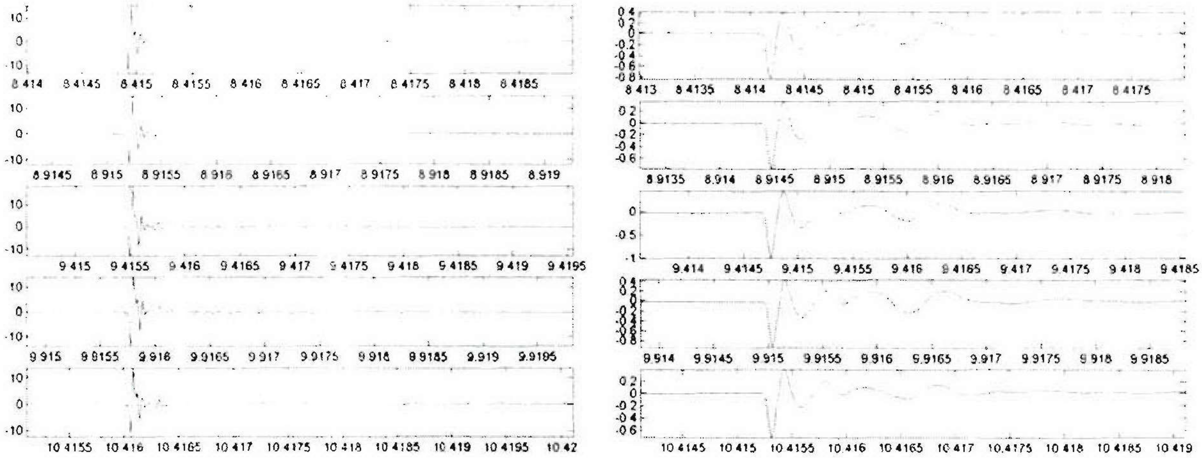


Figure 6: Five consecutive acoustic signals of the microphone in air (left) and buried in the sand (right).

3.2 Laser Doppler vibrometer

The acoustic signal results in a frequency modulation of the 455 kHz high frequency carrier as a result of the Doppler frequency shift $2v/\lambda$, where v is the velocity and λ is the wavelength of the laser. MATLAB was used to demodulate the high frequency signal in order to obtain the instantaneous velocity as a function of time.

The Nd:YAG laser was aimed at the center of mine 11 of which the center was 1 cm deep buried in the sand. Mine 11 is a test mine simulating the anti-tank mine TM62P. As a reference the Nd:YAG laser was also aimed at a position without a buried object. The demodulated signals are shown in Figure 7; the figures on the left and on the right are with and without mine, respectively. About 200 μs after the data acquisition AD card is triggered the laser pulse hits the sand. A clear response is visible due to the surface excitation. Clearly, the LDV measures the acoustic wave created by the laser pulse (first peaks). After about 50 μs another signal is measured as the result of the reflection of the acoustic wave from the mine top.[3] This delay corresponds quite well with the depth of 1 cm and an expected sound velocity of about 340 m/s.[5] If there is no mine beneath the laser spots only the first signal peaks are measured by the LDV.

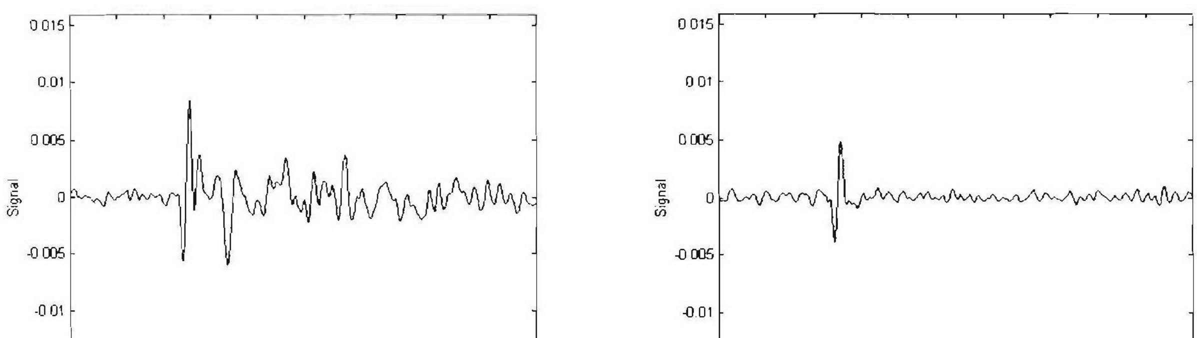


Figure 7: reflected vibration signal from mine 11 (TM62P) at 1 cm depth (left) and signal without mine (right).

The response of the soil shows large variations from shot to shot, both in the first (surface) peak as in the reflection from the test mine. These variations make the interpretation of the data difficult. It is not clear yet whether it is possible to extract more from the data than the approximate depth of a buried object. In addition, we have to be cautious in attributing the second peak as an echo of the buried mine. As shown previously in Figure 5, the high frequencies are

attenuated strongly in the sand. Since for a significant echo in a time scale of 50 μm we need high frequencies propagating in the sand, it is not clear whether the interpretation of an echo due to the buried mine is reliable.

3.3 Influence of laser parameters

The relative position of the excitation laser spot and the probe laser spot was investigated. It is not possible to have the spot of the probe laser at the same position as the spot of the excitation laser, since the excitation laser disturbs the probe laser. Figure 8 shows the LDV signal when the spots of the two laser beam overlap. The large peaks in the signal are caused by fast moving particles (sand, dust) that are projected from the surface due to the laser excitation.

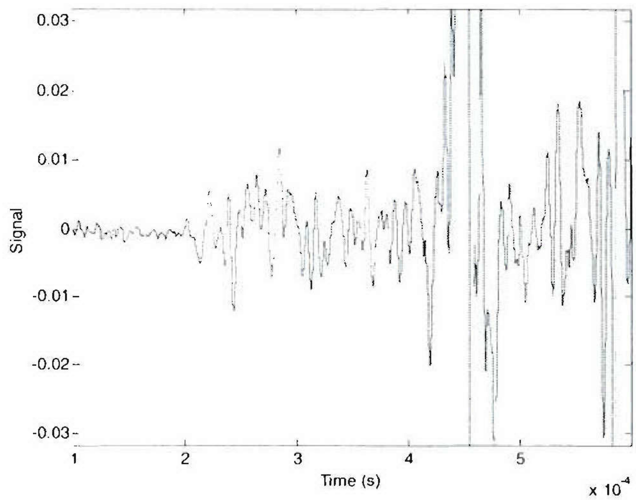


Figure 8: Disturbance of the LDV signal by the laser excitation.

For a reliable signal, it is required to separate the two laser spots. Figure 9 shows the LDV signal for various separations between probe and excitation laser spots in the situation without a buried object. The first peak is always at the same position and can be attributed to electrical interference of the excitation laser, which was located near the LDV system in these laboratory experiments. In addition, a different excitation laser was used from that in the field experiment with different electronics for the triggering. For the second peak, it is clear that an increased separation causes an increased delay. This second peak is the acoustic wave that propagates along the surface. Figure 10 shows the delay of the LDV signal peak as a function of distance between laser excitation spot and LDV probe spot. The slope of the straight line that connects the points corresponds to a velocity of 340 m/s, which corresponds to the speed of sound.

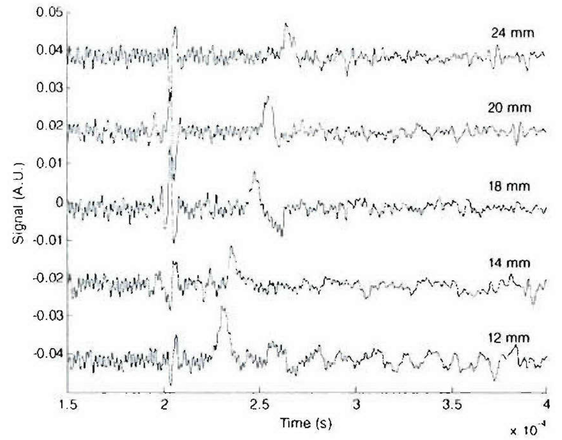


Figure 9: LDV signal for various separations between probe and excitation laser spots.

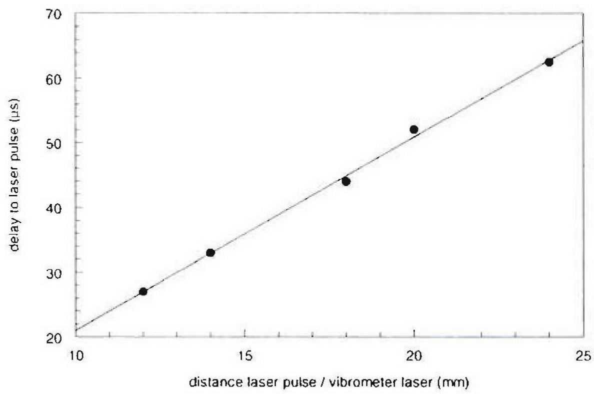


Figure 10: Delay of LDV signal as a function of spot separation.

Unfortunately, the shot-to-shot variation of the LDV signal is quite large and increases when a buried object is present. The LDV signals of Figure 10 were selected from many shots. Approximately 50% of the shots showed the peak in the LDV at the expected position. The other shots showed large disturbances in the LDV signal.

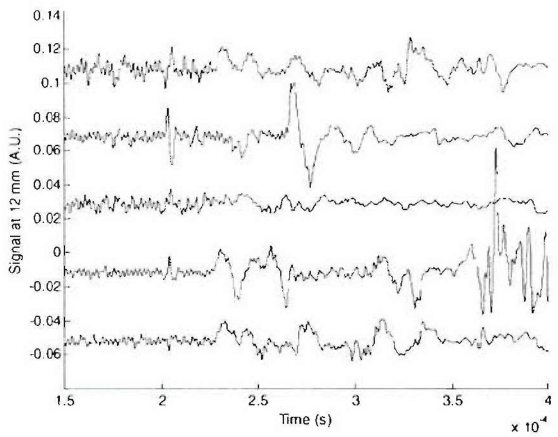


Figure 11: Shot-to-shot variation of the LDV signal WITH buried object.

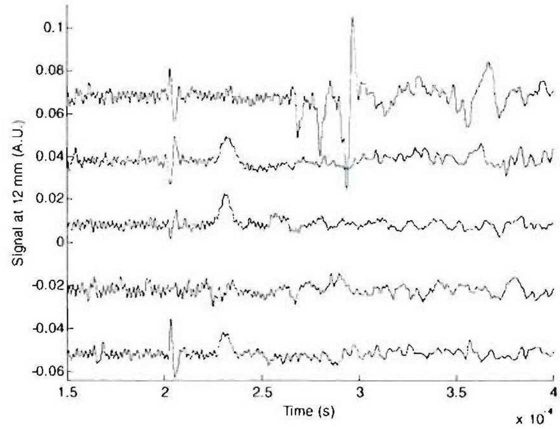


Figure 12: Shot-to-shot variation of the LDV signal WITHOUT buried object.

Figure 11 and Figure 12 show the shot-to-shot variation for the situation with and without a buried object. Both figures show results with the excitation and the probe laser spot at a separation of 12 mm. For some shots with a buried object, it is possible to see a peak at the expected position corresponding to the echo from the buried object. A discussion of these large variations is given in the next section.

4. DISCUSSION

4.1 Surface effects

The LDV system measures the velocity of the surface at the spot of the probe laser by determining the frequency shift with an FM receiver. Since we know that the Doppler shift is $2v/\lambda$, the signal before FM demodulation is given by

$$s(t) = A(t)\sin\left(2\pi f_C t + 2\pi\frac{2v}{\lambda}t\right) = A(t)\sin(2\pi f_C t + 2\pi\phi(t)),$$

where $A(t)$ is the amplitude, $\phi(t)$ is the time dependent phase, and f_C is the carrier frequency. FM demodulation is the time differentiation of the phase (ignoring the carrier frequency). It is clear from this equation that there is a non-linear relation between two laser-light reflecting points, i.e. the FM demodulation of $s_1(t)+s_2(t)$ is not the time differentiation of $\phi_1(t)+\phi_2(t)$. This means in practice that areas with different velocities within the laser spot lead to a distorted acoustic signal. Therefore, the laser spot is focused to obtain a clear acoustic signal. However, the consequence is that the LDV signal is very sensitive to local effects and only shows the vibration of a very small surface spot and not the average of the surface vibration as in the microphone experiments that measure pressure variations caused by the entire vibrating surface.

Another surface effect that is typical of laser sensing systems is the speckle effect. Due to the high coherence of the laser light the contribution of surface scatterers is added coherently. In imaging systems this leads to granular images, i.e. images with small grains of light and dark spots (speckle). In an LDV system this speckle effect is the cause of extra noise.

Finally, the LDV system is sensitive to fast moving debris from the laser excitation. This effect is absent in microphone measurements.

4.2 LDV versus microphone detection

Detection of the acoustic signal from a buried using an LDV instead of a microphone shows the prospect of stand-off detection using laser excitation for the generation of the acoustic signal and an LDV for detection of the acoustic signature. An additional anticipated advantage of an LDV over a microphone is that an LDV measures the vibration directly at the surface level while the microphone measures in air above the ground. Therefore, the LDV is expected to be more sensitive and to show fewer disturbances from other acoustic noise sources.

However, we have shown that using an LDV gives large shot-to-shot variation, which can be attributed to surface effects. It is not clear how these effects can be reduced in order to make the combination laser excitation and LDV into a reliable system for acoustic landmine detection.

5. CONCLUSIONS

A field test and laboratory experiments of acoustic landmine detection (ALD) were performed. Laser excitation was used for the generation of the acoustic signal and Laser Doppler vibrometry was used to detect the acoustic signature of the buried surrogate mine.

It was found that the acoustic signal generated by the laser excitation has a high reproducibility from shot to shot as was registered by a microphone above the excitation. A buried microphone showed that the acoustic signal is coupled into the ground with a high reproducibility. The LDV sensor showed consistent results for the acoustic signal from the surface. However, there was a large shot-to-shot variation. This variation between different shots from the excitation laser made analysis of the acoustic signal from a buried mine unreliable.

The shot-to-shot variation of the LDV system is attributed to surface effects that are dominant in an LDV system but are absent for microphones. These surface effects are local variations due to the small laser spot, speckle effects, and debris from the laser excitation that pass the LDV probe beam. These surface effects should be minimized in order to obtain a reliable ALD detection system.

REFERENCES

1. J.C. van den Heuvel, V.Klein, P. Lutzmann, F.J.M. van Putten,M. Hebel, and H.M.A. Schleijpen, "Sound wave and laser excitation for acousto-optical landmine detection", in Proc. SPIE, Detection and Remediation Technologies for Mines and Minelike Targets VIII, Orlando (FL), USA, April 2003.
2. W. de Jong, H. A. Lensen, and Y. H. L. Janssen, "Sophisticated test facility to detect land mines," in Proc. SPIE Vol. 3710, Detection and Remediation Technologies for Mines and Minelike Targets IV, A. C. Dubey and J. F. Harvey, eds., pp. 1409–1419, (Orlando (FL), USA), Apr. 1999.

3. W. Li, C.A. DiMarzio and S.W. McKnight, "Laser-induced Acoustic Detection of Shallow-Buried Objects", Proc. SPIE Vol.3752, July 1999.
4. S.W. McKnight et.al., "Laser-induced acoustic generation for buried object detection", Proc. SPIE Vol. 4038 (April 2000).
5. S.W. McKnight, J. Stott, C.A. DiMarzio, R Cleveland, R. Roy, "Laser-induced acoustic imaging of buried land mines: experiment and modeling", SPIE vol 4394, pp. 627-633.
6. Charles A. DiMarzio, et. al., Toward a Laser-Based, "Non-Contact Acoustic Landmine Imager"; Proc. SPIE Vol. 4038 (April 2000).

REPORT DOCUMENTATION PAGE
(MOD-NL)

1. DEFENCE REPORT NO (MOD-NL)	2. RECIPIENT'S ACCESSION NO	3. PERFORMING ORGANIZATION REPORT NO
TD2005-0362		TNO_DV1 2005 A044
4. PROJECT/TASK/WORK UNIT NO	5. CONTRACT NO	6. REPORT DATE
015.31606	A01KL876	January 2006
7. NUMBER OF PAGES	8. NUMBER OF REFERENCES	9. TYPE OF REPORT AND DATES COVERED
58 (incl appendices, excl RDP & distribution list)		Final

10. TITLE AND SUBTITLE

Landmine detection using laser vibrometry

11. AUTHOR(S)

Dr. J.C. van den Heuvel
Ir. A.C. van Koersel
Ing. F.J.M. van Putten
Dr. ir. H.M.A. Schleijpen

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Defence, Security and Safety, Location The Hague , P.O. Box 96864 , 2509 JG The Hague , The Netherlands
Oude Waalsdorperweg 63, The Hague, The Netherlands

13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES)

Ministry of Defense, Royal Netherlands Army

14. SUPPLEMENTARY NOTES

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret..

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

Acoustic Landmine Detection (ALD) using a laser vibrometry was studied using two acoustic ground excitation methods: acoustic (loudspeaker) excitation (AE) and laser excitation (LE). AE is suitable for detecting buried landmines but is a slow technique. A faster AE method based on a CMOS camera was proposed but not studied further. LE is potentially a faster technique but suffers from surface effects. An important surface effect is the relaxation of the surface after the disturbance by the laser excitation pulse. This relaxation lasts for more than 4 ms in the vicinity of the laser-excitation spot. Due to these surface effects, LE does not seem to be a viable technique in combination with laser vibrometry.

16. DESCRIPTORS	IDENTIFIERS
Lasers Landmine Mine detection Laser vibrometry	

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
Ongerubriceerd	Ongerubriceerd	Ongerubriceerd

18. DISTRIBUTION AVAILABILITY STATEMENT	17d. SECURITY CLASSIFICATION (OF TITLES
Unlimited Distribution	Ongerubriceerd

Distributionlist

Onderstaande instanties/personen ontvangen het managementuittreksel en de distributielijst van het rapport.

4 ex.	DMO/SC-DR&D
1 ex.	DMO/ressort Zeesystemen
1 ex.	DMO/ressort Landsystemen
1 ex.	DMO/ressort Luchtsystemen
2 ex.	BS/DS/DOBBP/SCOB
1 ex.	MIVD/AAR/BMT
1 ex.	Staf CZSK
1 ex.	Staf CLAS
1 ex.	Staf CLSK
1 ex.	Staf KMar
1 ex.	TNO Defensie en Veiligheid, Algemeen Directeur, ir. P.A.O.G. Korting
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Operaties, ir. C. Eberwijn
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Kennis, prof. dr. P. Werkhoven
1 ex.	TNO Defensie en Veiligheid, Directie Directeur Markt, G.D. Klein Baltink
1 ex.	TNO Defensie en Veiligheid, vestiging Den Haag, Manager Beleidsstudies Operationele Analyse & Informatie Voorziening (operaties), drs. T. de Groot
1 ex.	TNO Defensie en Veiligheid, vestiging Rijswijk, daarna reserve Manager Bescherming, Munitie en Wapens (operaties), ir. P.J.M. Elands
1 ex.	TNO Defensie en Veiligheid, vestiging Rijswijk, Manager BC Bescherming (operaties), ir. R.J.A. Kersten
1 ex.	TNO Defensie en Veiligheid, vestiging Soesterberg, Manager Human Factors (operaties), drs. H.J. Vink

Onderstaande instanties/personen ontvangen een volledig exemplaar van het rapport.

1. DMO/SC-DR&D
2. DMO/DR&D/Kennistransfer
3. DMO/DR&D/Kennistransfer
4. KL GOC/KC, Maj. B.W. de Groot
5. TNO Defensie en Veiligheid, vestiging Den Haag,
   Manager Waarnemingssystemen (operaties), dr. M.W. Leeuw
6. Bibliotheek KMA
7. Bibliotheek KMA
8. Bibliotheek KMA
9. Archief TNO Defensie en Veiligheid, in bruikleen aan Dr. J.C. van den Heuvel
10. Archief TNO Defensie en Veiligheid, in bruikleen aan Ir. A. C. van Koersel
11. Archief TNO Defensie en Veiligheid, in bruikleen aan Ing. F.J.M van Putten
12. Archief TNO Defensie en Veiligheid, in bruikleen aan Dr. ir. H.M.A. Schleijpen
13. Documentatie TNO Defensie en Veiligheid
14. Reserve